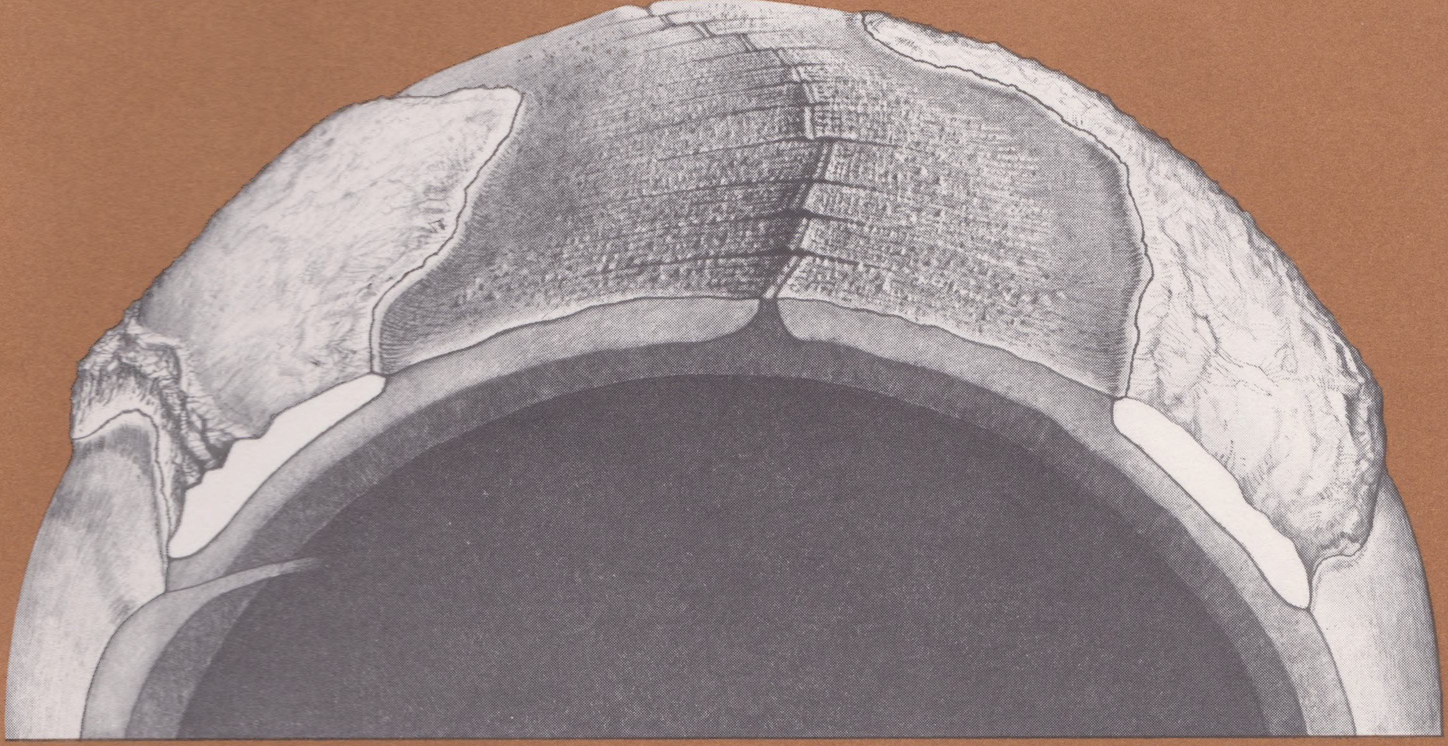
S101 Units 6 and 7

THE OPEN UNIVERSITY

Science: A Foundation Course

Plate Tectonics



A Revolution in the Earth Sciences

The Open University

Science: A Foundation Course

Units 6 and 7
Plate tectonics: a revolution in the Earth sciences

Prepared by the Science Foundation Course Team

The Open University Press

SCIENCE

S101 Course Team List

A note about the authorship of this text

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2.1

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Comment

In this Table, the terms listed in the first column (Assumed from general knowledge) are used in the text without being explained or defined. If some of them are new to you, please refer to any dictionary; the simple explanations you will find there will be quite sufficient.

Assumed from general knowledge	Defined in a previous Unit	Unit No.	Developed in this Unit	Page No.	Introduced in this Unit, but developed further in later Units	Unit No.
continents	asthenosphere	4	*Major features of the Earth's surface*		igneous, sedimentary and metamorphic processes at plate boundaries	27
fossil	basalt	4*	abyssal plain	13	methods of dating rocks	26
oceans	continental crust	4	continental rise	13	radioactivity	10/11
palaeontology	convection	4	continental shelf	13		
topography	core	4	craton	AV†		
	earthquake epicentre	4	continental slope	13		
	earthquake first-motion studies	4	guyot	34		
	Earth's pole of rotation (geographic pole)	4/5	island arc	AV†		
	effusive volcanic activity	4*	mountain belt	13		
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	seismic zones	4				

TABLE A List of terms and concepts used in Units 6 and 7 continued

Assumed from general knowledge	Defined in a previous Unit	Unit No.	Developed in this Unit	Page No.	Introduced in this Unit, but developed further in later Units	Unit No.
			Continental drift			
			Evidence for continental drift:			
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			fit of past faunal and floral distributions	22		
			polar wandering curves	31		
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			geometry of spreading centres and transform faults	54, 56, 77		
			poles of plate rotation	56		
			subduction zones	58		
			Types of plate margin:	60, 78		
			conservative	60		
			constructive	63		
			destructive	66		

* Introduced in the Audio-vision sequence associated with Unit 4, entitled 'The origin of rocks' (AC 90).

† Introduced in the Audio-vision sequence associated with Units 6 and 7, entitled 'Crustal patterns' (AC 90).

Study guide

Units 6 and 7 cover one topic, the twentieth-century revolution which has taken place in our understanding of the workings of the Earth's crust. The two Units have been written without an obvious break because the subject matter itself does not divide conveniently into two separate Units. This is the first example you have met in S101 of a 'double Unit'; there will be others later in the Course, for example Units 10 and 11. Units 6 and 7 should take you two weeks to study; by the end of the first week you should have completed sections 1–4.3, including study of the Audio-vision sequence 'Crustal patterns' (AC 90). The visual component of this sequence consists of the *World Ocean Floor* chart, and Figures 7–11, which fold out from the back of the Unit Main Text, so you will not need to use your filmstrip viewer.

Before you start work on Units 6 and 7 it is essential that you are thoroughly familiar with the terms and concepts introduced in the Audio-vision sequence associated with Unit 4, entitled 'The origin of rocks' (AC 90). You should have studied this material when completing Unit 4, but you may feel the need to revise it briefly now. To help you judge whether any revision is necessary, make sure that you understand the meaning of the terms and concepts listed in the second column of Table A.

While studying Units 6 and 7 it will help if you can consult the *World Ocean Floor* chart with ease, and not have to keep unfolding it. Use of this chart is absolutely essential when reading Section 2.3, *Earth patterns.*

Once you have finished Section 2, you should use the Audio-vision sequence associated with these Units, entitled 'Crustal patterns' (AC 90), because it gives the answers and provides follow-up discussion to a series of questions posed in Section 2. Note that no answers to these are given in this text, although you can revise this material by completing SAQs 1–5.

You will find that many of the illustrations in these two Units are accompanied by fairly long captions. Generally, these illustrations and captions are used to give a comprehensive description of, say, a feature of the Earth's surface, or a particular scientific concept. The Main Text discusses the significance of such features and concepts, and relates them to the historical development of aspects of the Earth sciences over the past 60 years. So the 'story' that provides the framework for Units 6 and 7 lies in the Main Text, but most of the items you will want to concentrate on when revising are covered by the illustrations.

There are no Home Experiments associated with Units 6 and 7. The two TV programmes deal with continental drift (TV 06) and plate tectonics (TV 07). The Radio programme (Radio 03) discusses historical aspects of the initial rejection and final acceptance of the continental drift hypothesis.

1 Introduction

In earlier Units we have examined how a number of basically simple observations concerning the properties of the Earth can be incorporated into *models* of its internal structure and composition. But the scale of the models used in Units 4 and 5 is so vast that it is almost beyond the scope of human imagination. In Units 6 and 7 we shall continue to make some basic observations about our planet, but this time examine the nature of the Earth's outer skin, the lithosphere, and its familiar surface expression, the continents and oceans. In addition to discussing observations, hypotheses and models, we shall also explain how ideas concerning the workings of the crust have changed over the past 60 years, not just because this is a fascinating story, but because it illustrates science as a human activity, and shows how scientific advances are often related to social, political and technological developments.

In Section 2, you will study the Earth's surface features using a number of maps printed with the text, and the large *World Ocean Floor* chart that accompanies these Units. This will lead to a discussion of the major vertical and lateral changes in the composition and structure of the crust. When you have finished Section 2, you should *be able to describe the major features of the Earth's crust and its surface.*

In Section 3, we shall examine how ideas concerning the origin of continents and oceans have changed over the past 60 years, and, in Section 4, we will show how the phenomena discussed in Section 2 are explained today by the model known to Earth scientists as 'plate tectonics'. When you have finished Sections 3 and 4, you should *be able to describe the theory of plate tectonics, and summarize the evidence and lines of reasoning that underpin it.*

Once you have been introduced to plate tectonics, you may be surprised that earlier ideas, especially those concerning continental drift, were not accepted 60 years ago. But, as you will see when you study the detailed story concerning the recent revolution in the Earth sciences, progress in science does not happen in a vacuum. It is intimately linked to developments not only in other disciplines, but to technological and political events as well. In this respect, there is nothing unique about the history of plate tectonics, for advances in other fields which you will meet during the Course also happened against the background of contemporary events—and some of these may even be termed 'scientific revolutions'. So, when you have completed Section 3 and Section 6 you should *understand how the development of the plate tectonic theory was influenced by technological and political developments, and why it can be considered as a 'scientific revolution'.*

2 Crustal patterns

Study comment Allow about one hour for a first read through of Sections 2.1 to 2.3.

2.1 Why are there continents?

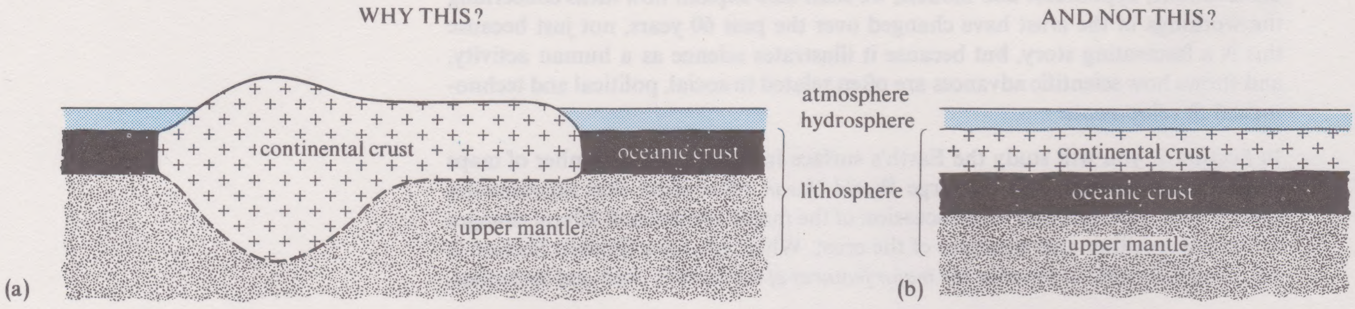


FIGURE 1 When the structure of the outer 'skin' of the Earth is examined, the idea of a model consisting of concentric shells breaks down. Instead of granitic and basaltic crust and the overlying hydrosphere forming successive shells of uniform thickness, the base of the crust mirrors, in an exaggerated way, the surface relief of the Earth (see also Unit 4, Figure 41).

In Unit 4, evidence was presented that supported a simple multi-shelled model for the internal structure of the Earth. The Earth's core is divided into inner and outer parts, and beyond it there are further concentric shells of mantle and crust. You might expect this concentric pattern to continue into the detailed structure of the Earth's outer skin. But this skin, though consisting of basaltic and granitic material which is covered by a liquid hydrosphere and gaseous atmosphere, does not show a regular concentric structure (see Figure 1). Instead, we find that the lighter granitic material is dotted about the Earth's surface in slabs of irregular thickness (see Unit 4, Figure 41), with the hydrosphere occupying the hollows in between, instead of being spread uniformly over the globe as a single, shoreless ocean*. This irregular distribution of crustal materials implies that something must have separated the lighter continental crust into separate slabs at some stage during the Earth's history.

We know that continents were formed very early during the Earth's history. As you will see in Unit 28, the Earth is considered to have formed approximately 4 500 Ma (4.5×10^9 years) ago—a time span almost impossible to imagine. The oldest rocks found on the continents have been dated** at 3.8×10^9 years. So it seems that continental crust has existed for a vast period of time. The present volume of land above sea-level is about $13 \times 10^7\,\text{km}^3$, and it is estimated that $13.6\,\text{km}^3$ of rock material is removed to the oceans every year (see Figure 2). If this were the only geological process operating on the continents, how long would they last? If the erosion process continued at the same rate until they were planed flat†, the continents would be covered by the sea in slightly less than ten million years—yet they have lasted thousands of millions of years (over two orders of magnitude longer than the estimate suggests). So clearly other processes must have operated to maintain the existence of continents through the vast span of the Earth's history.

* If all the water in the present-day oceans were spread uniformly over the Earth as depicted in Figure 1b the single, shoreless ocean would be 2.6 km deep.

** Methods of determining the age of rocks will be discussed in Unit 26.

† In reality, it would not continue at the same rate but would slow down because, as the relief of the continents was diminished, rivers would flow more slowly, and so carry less material.

FIGURE 2 Vast amounts of material are removed from the continents and deposited in the oceans every year, yet most of the continental crust has remained above sea-level for thousands of millions of years. Processes operating to remove rock material from the continents to the ocean basins involve the interaction of air, water, temperature changes, and solar and gravitational energy. Heat from the sun leads to evaporation of water from the oceans, which is precipitated over land areas, whence it returns to the oceans via lakes, rivers and underground flow.

(a) Masses of rock debris loosened by alternative freezing and thawing have accumulated beneath the steep valley side. Gravity alone was almost entirely responsible for their movement after initial loosening from the parent rock.

(b) Coastal erosion. Wave energy (derived from the sun via winds generating waves) has resulted in the cliff line receding. Ribs of steeply inclined rock strata stand out above the beach sands, which are derived from the breakdown of solid rock.

(c) Deposition of sands and muds in an estuary. Reduction in the velocity of river currents as they reach the sea causes rock debris (that is, sand, silt and mud) to be deposited. In the future, if these deposits were to be buried, they would become 'new' rocks.

The discussion in the previous two paragraphs provides a brief insight into the problems posed by the nature and distribution of the features of the Earth's solid surface. It is clear that processes have operated, and still are operating to maintain the relief of the continental crust, a situation that is in marked contrast to that on the Earth's nearest companion, the Moon (see Figure 3). The lunar surface not only looks different from that of our home planet, but it is dominated by immensely old rocks (older than 3 000 Ma). The Moon's surface has altered little over that vast period, whereas the Earth's outer skin has been re-worked by geological processes (such as those described in the Audio-vision sequence associated with Unit 4, 'The origin of rocks') time and time again so that over three-quarters of its surface is less than 200 Ma old. The processes that caused such re-working are the subject of this Block and much of Units 26–28.

To begin to understand some of these processes we must now examine in more detail the surface features of the solid Earth.

FIGURE 3 The ages and form of the surface features of the Earth and Moon are completely different, reflecting their different geological histories.

(a) A deeply eroded region of sedimentary rocks (about 100 Ma old) shows a layered structure that was originally horizontal but has been deformed by Earth movements.

(b) The Moon's surface is over 3 000 million years old, and suffered extensive cratering early in its history. These ancient features have been preserved because the Moon has not experienced crustal movements of the kind seen on the Earth, and also because there is no erosion by wind and water.

2.2 Surface features of the Earth

2.2.1 Heights and depths

At first sight there does not seem to be much order about the overall distributions of land and sea on our globe. But one hemisphere contains most of the land areas, and the other most of the ocean areas (see Figure 4). Taken as a whole, the planet is dominated by water, 71 per cent of it being covered by seas.

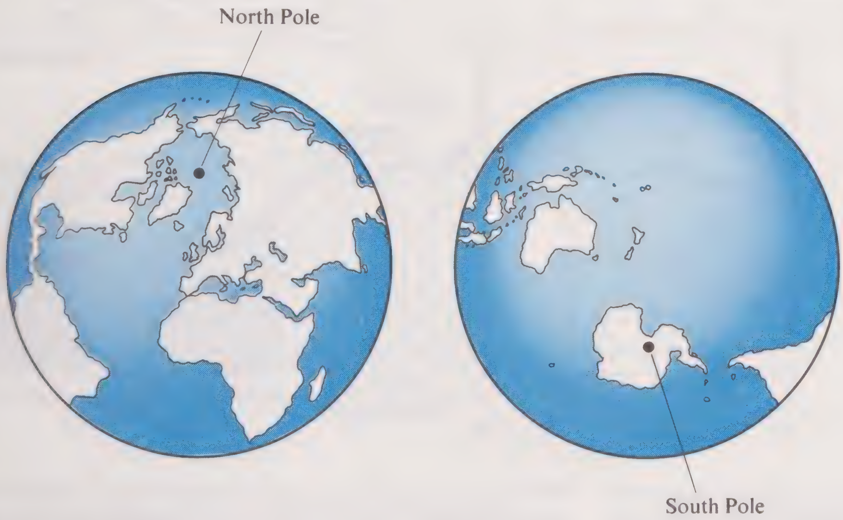


FIGURE 4 The Earth's 'continental' and oceanic hemispheres. The non-uniform distribution of continents is highlighted in these two views of the Earth, one portrayed from directly above the British Isles, the other from above New Zealand.

So the distribution of land and sea is not uniform over the Earth's surface; but what about the distribution of heights both above and below sea-level: what pattern would you expect these to show? The *simplest* distribution would be one in which the bulk of the Earth's solid surface lay just above or just below sea-level, with progressively less at higher altitudes and greater ocean depths. This is certainly the simplest pattern imaginable, but what really happens? Table 1 shows the results of surface area measurements on a map of the Earth showing land and submarine contours at one kilometre intervals both above and below sea-level. The second column of this Table shows that the simple pattern does not apply, for there is not just one 'peak', but two.

TABLE 1 The distribution by height and depth of the Earth's solid surface. The data show that the dominant heights and depths are not clustered around sea-level as might be expected, but that they occur as two distinct 'peaks'.

Height or depth interval/km	Percentage of total surface area of the Earth (total = $51 \times 10^7\,km^2$)	Cumulative percentage area*
Above sea-level		
5	0.1	0.1
4–5	0.4	0.5
3–4	1.1	1.6
2–3	2.2	3.8
1–2	4.5	8.3
0–1	**20.8**	29.1
Below sea-level		
0–1	8.4	37.5
1–2	3.1	40.6
2–3	6.1	46.7
3–4	14.7	61.4
4–5	**22.6**	84.0
5–6	15.0	99.0
6–7	0.9	99.9
7–12	0.1	100.0

* Cumulative area is found by successively adding the entries in the middle column. Thus the cumulative area at the 2–3 km interval is the total of the first four entries in the middle column; it means that 3.8 per cent of the Earth's surface is higher than 2 km above sea-level. Similarly the first entry below sea-level means that 37.5 per cent of the Earth's surface is higher than 1 km below sea-level.

The distribution of areas of the Earth's surface at different altitudes is demonstrated with much more impact if the data in Table 1 are presented in graphical form, as shown in Figure 5. This Figure leaves no doubt that the solid Earth's surface is dominated by two principal levels, one characteristic of continental regions, the other of oceans.

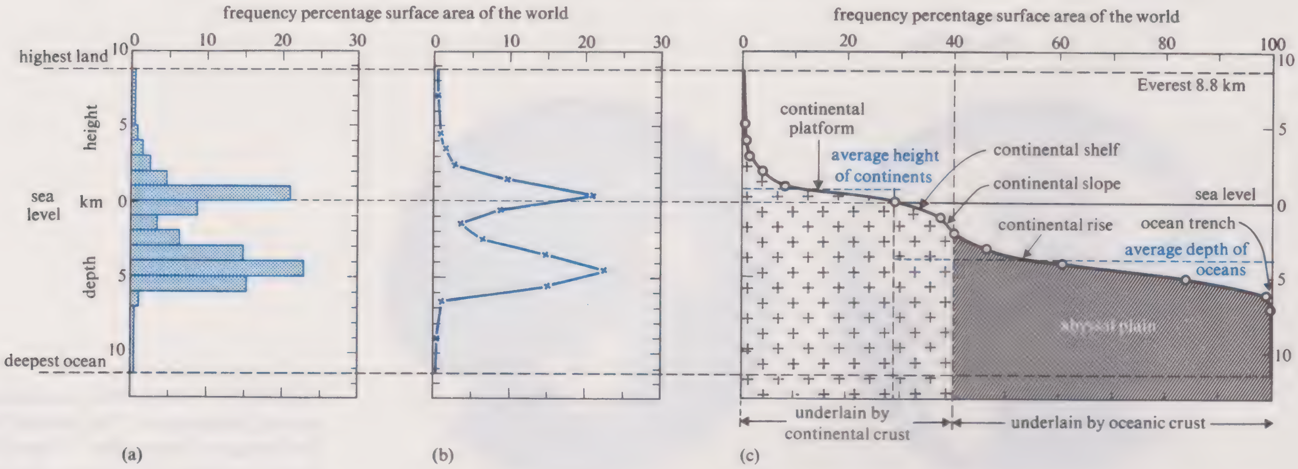


FIGURE 5 Three different methods of graphically illustrating the distribution of the areas of the solid Earth's surface, using the data given in Table 1. All the methods show the two principal levels, one characteristic of the continents, the other of the oceans.

(a) A *histogram* or bar-chart in which the height (and hence area) of the bar is proportional to the percentage represented.

(b) A *frequency curve*, in which the percentages given in Table 1 are plotted as single points (for example, the value for the 1–2 km interval plotted at its mid-point of 1.5 km, for the 2–3 km interval at 2.5 km, and so on, and the points joined by a smooth curve. This method of plotting approximates much more closely to the true distribution, for clearly the Earth's topography is not made up of a series of steps as depicted in Figure 5a.

(c) A cumulative frequency curve, plotted in the same way as Figure 5b but using the data from the third column of Table 1.

Note The usual convention when constructing histograms, frequency curves and cumulative frequency curves is to plot percentages vertically, and not horizontally as in these examples. The reason for breaking the convention in this case is self-evident—especially for Figure 5c.

Do you recall a fundamental difference between the nature of continental and oceanic crust?

Continental crust is less dense than oceanic crust (remember the results of the Home Experiment you completed in Unit 4). Thus it appears that the two principal crustal levels shown in Figure 5 are underlain by material of different densities: basaltic material (similar to Specimen S3 in your Home Experiment Kit) under the oceans and granitic material (Specimen S1) which forms much of the upper continental crust. This surface shape suggests a model in which the crust is floating on the mantle, with the lighter continental material standing higher—analogous to blocks of wood of different densities submerged to different depths when floating on water.

We shall return to the significance of this model later; for the moment it is sufficient to emphasize that for a geologist, the terms 'continental' and 'oceanic' have a different meaning from those adopted by the layman. 'Oceanic' for the layman has connotations of water, but to the geologist the term is concerned with the part of the crust that has a density of $2\,800$–$2\,900\,\mathrm{kg\,m^{-3}}$ as opposed to a density of $2\,600$–$2\,800\,\mathrm{kg\,m^{-3}}$ for granitic continental crust. It so happens that the hydrosphere covers the boundary between oceanic and continental crust (see Figure 5c); indeed, about 25 per cent of continental crust is covered by water.

2.2.2 Surface features of oceans and continents

Having established that there is a fundamental difference between the crust underlying continents and oceans, we can now proceed to examine their features in more detail with the aid of the *World Ocean Floor* chart. When you look at this chart for the first time, the surface relief of both the continents and oceans appears rather complex, but as you work through the next few pages you will see that there is a considerable degree of order in the distribution of certain features.

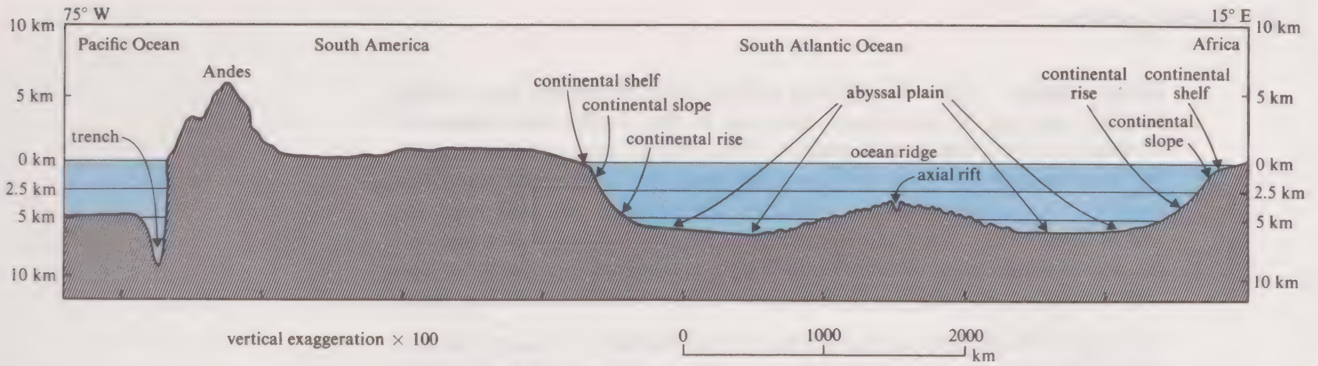


FIGURE 6 Cross-section to show the surface of the Earth's crust between South America and Africa. You should locate the line of this section on the *World Ocean Floor* chart.

First you need to 'get your eye in' when using the chart. To do this, locate the line of section shown on Figure 6, which runs from the Pacific Ocean west of South America (from a point south of Salvador) to the African coast south of Luanda. Figure 6 identifies the features of continental margins and ocean basins *which you should be able to identify on any part of the chart.* Spend some time studying the chart, and try to answer the following questions:

> How are continental mountain belts distributed about the globe? Look for two main 'belts' of such mountains; is one of these associated with a particular feature in the ocean basins?
>
> How extensive is the distribution of ocean ridges? Do the ridges display any unusual features that make them distinct from continental mountain ranges?

Before reading on, you should make a serious attempt to answer these questions.

2.2.3 Continental mountain belts

mountain belts

There are two main belts. The first borders the Pacific Ocean: in the east it consists of the Rockies and Andes, and in the west of a more complicated and discontinuous pattern of mountains in Kamchatka, Japan, the Philippines, New Guinea, the Great Dividing Range of Australia and the Southern Alps of New Zealand. This circum-Pacific mountain belt is closely associated with ocean trenches. The second major mountain belt is that of the Alpine–Himalaya chain which runs approximately west–east from the Mediterranean, and is largely enclosed *within* continental masses.

2.2.4 Ocean ridges

ocean ridge system

axial rift

The ocean ridge shown in Figure 6, which is termed the Mid-Atlantic Ridge (note it is only in the Atlantic that the ridge is situated midway between the flanking continental slopes), can be traced northwards through and beyond Iceland, south-eastwards into the Indian Ocean Ridge, and onward into the East Pacific Ridge which disappears northward under the North American continent. You may be surprised to learn that the ocean ridge system is the Earth's largest mountain chain, extending for more than 50 000 km, having an average width of 1 000 km, and rising by as much as 5 km (but usually only 2 km) above the flanking abyssal plains. Ocean ridges are formed by processes vastly different (but not unrelated, as we shall see) from those that have thrown up continental mountains, and these differences are reflected by some of the surface details that are large enough to be depicted on the *World Ocean Floor* chart. Most of the ridges are gashed by numerous fractures that trend perpendicular to their axes, and the axes themselves are marked by a central 'axial rift valley', as shown in Figure 6. Moreover, the ocean ridges are roughly *symmetrical*, with the topography of one flank being the mirror image of the other across the central rift valley*. The discovery of these features was of immense significance in explaining the origin of nearly all the major features of the Earth's surface, as we shall see once we have examined more data concerning the oceans and continents.

* This is not true for small-scale features, but only for the large features depicted on the *World Ocean Floor* chart.

2.3 Earth patterns

Study comment You will probably need to spend about one hour on this Section, and up to two hours listening to the Audio-vision sequence 'Crustal patterns', that accompanies it. You should write notes summarizing your answers so that you can refer back to them when using this Audio-vision sequence. While studying this Section, you will need the *World Ocean Floor* chart and Figures 7–11 (which fold out from the text at the end of these Units) clearly visible to help you answer the questions. You may need a lens to help you read the print on the *World Ocean Floor* chart.

If you have to divide your study time on this Section into more than one period, we suggest you stop after answering the questions, and spend a later session working through the Audio-vision sequence; finally, you should complete the Section by answering SAQs 1–5 (on pages 16–18).

In Section 2 some indications of a definite pattern to the distribution of the Earth's surface features began to emerge.

1 The topography of ocean ridges is symmetrical, with one side mirroring the other.

2 In the Atlantic, the ridge is generally equidistant from the flanking continents.

3 The Pacific Ocean is rimmed by a system of continental mountains and ocean trenches.

In Sections 2.3.1–2.3.3, *you* will look for further patterns, involving the age distribution of rocks and the occurrence of active volcanoes and earthquakes, by answering ten questions. You should answer these questions using the information presented in the *World Ocean Floor* chart and in Figures 7–11. The answers to the questions, and further comments, are given in the Audio-vision sequence 'Crustal patterns'. Therefore, you should make notes as you answer each of the questions so that you can check your conclusions with those given in this Audio-visual sequence.

2.3.1 Continental patterns

Note Figures 7–11 are on a fold-out sheet at the end of these Units.

1 What kind of topography is displayed by areas of the continents exposing the oldest rocks; are they relatively flat, or relatively rugged? (Look at Figure 7 and the *World Ocean Floor* chart, which also gives an indication of the topography of the continents.)

2 Are these old areas geologically active, or inactive (that is, are they characterized by volcanic and seismic activity)? (Look at Figures 9, 10 and 11.)

3 Are mountainous areas (above 3 000 m) such as the Alps, Andes, Himalayas and Rockies, composed of relatively young or old rocks (bearing in mind that the Earth is around 4 500 Ma old)? (Look at the *World Ocean Floor* chart and Figure 7.)

4 Do you notice any relationship between those mountain ranges that have volcanism and those that do not, and their proximity to ocean basins? (Look at Figure 9 and the *World Ocean Floor* chart.)

2.3.2 Oceanic patterns

5 What is the relationship between the topography of the Atlantic Ocean and the ages of the crust that floors it? (Look at the *World Ocean Floor* chart and Figure 8.)

6 Do you notice any relationship between oceanic topography and the distribution of seismic and volcanic activity (for example, are ridges associated with a particular kind of activity, and trenches with another)? (Look at the *World Ocean Floor* chart and Figures 9, 10 and 11.)

7 What are the differences between the Atlantic and Pacific Oceans in terms of:

(a) the symmetry of the topographic features they exhibit (is one side roughly the mirror image of the other)? (Look at the *World Ocean Floor* chart.)

(b) the relative rarity of any feature in one ocean as compared to the other (for example, are trenches rare in one ocean compared to the other)? (Look at the *World Ocean Floor* chart.)

(c) the features exhibited by the margins of the continents that border them? (You should consider continental and oceanic topography, ages of rocks, seismic and volcanic activity. Look at the *World Ocean Floor* chart and Figures 8, 9, 10 and 11.)

2.3.3 Contrasts between the features of continental and oceanic crust

8 What is the difference between the distribution of ages of rocks on the continents and oceans in terms of:

(a) the range of ages? (Give figures in hundreds of millions of years.)

(b) the geometric patterns of the distributions (simple versus complex, linear versus concentric, etc.)? (Look at Figures 7 and 8.)

9 What is the difference between the predominant type of volcanic activity of the continents and of the oceans? (Look at Figure 9.)

10 What, if any, is the difference between the depth of earthquake foci beneath the continents and the oceans? (Look at Figures 10 and 11.)

When you have answered these questions, listen to the Audio-vision sequence 'Crustal patterns' to check whether you were correct. This sequence discusses the data presented in Figures 7–11 and the *World Ocean Floor* chart in some detail.

Before listening to the tape, you should locate the following features on the chart (we have included approximate latitude and longitude positions of the lesser known features and there is also a key to the *World Ocean Floor* chart on page 83 to help you find them):

	Approximate longitude	Approximate latitude
South America		
Africa		
Newfoundland		
Mid-Atlantic Ridge		
Andes		
Alps		
Himalayas		
Rocky Mountains		
Mediterranean Sea		
Black Sea		
Hudson Bay		
Caribbean Sea		
Falkland Islands	60° W	50° S
South Sandwich Trench	25° W	60° S
Alaska		
Anchorage	155° W	65° N
Aleutian Trench (NW Pacific)	160° E	55° N
Kuril–Kamchatka Trench (West Central Pacific)	140–160° E	40–55° N
Japan*		
Mariana Trench (West Central Pacific)	145° E	10–20° N
Kermadec–Tonga Trench (West Central Pacific)	170–180° W	10–40° S
New Zealand*		
Puerto Rico Trench	60° W	15° N

2.4 Objectives of Section 2

Now that you have completed Section 2, you should be able to:

(a) Define in your own words, illustrate by sketches, or recognize correct definitions or illustrations of the following (the most important items are shown in italics): *continent*, *continental crust*, continental rise, continental slope, continental shelf, craton*, *mountain belt*, *ocean*, *oceanic crust*, *ocean trench*, *ocean ridge*, abyssal plain, island arc*, *seismic zones*, volcanic zones (including effusive and explosive zones of activity**).

(b) Explain why the continued existence of continents for at least 3 000 Ma implies a mobile outer part to the Earth.

(c) Describe the difference between the layman's concept of oceans and continents and that understood by Earth scientists.

(d) Describe the major patterns shown by the Earth's topographic features, ages of continental and oceanic rocks, and the distribution of seismic and volcanic activity.

Now complete the following SAQs to check your achievement of these objectives.

SAQ 1 (*Objective* (*a*)) Label the section shown in Figure 12 to show the following features:

A continental shelf
B continental slope
C continental rise
D abyssal plain
E ocean ridge
F axial rift valley

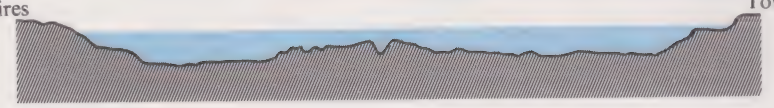


FIGURE 12 For use with SAQ 1.

SAQ 2 (*Objective* (*a*)) Complete Table 2 (opposite) to describe the principal features of the Earth's crust.

SAQ 3 (*Objective* (*b*)) In two sentences, state why the existence of continents with mountain ranges implies a mobile outer part to the Earth.

SAQ 4 (*Objective* (*c*)) Explain how the frequency distribution curve and the cumulative frequency distribution curve for the elevations of the solid Earth's surface can be used to explain the difference between the layman's and geologist's concept of continents and oceans.

SAQ answers begin on p. 79.

* Defined in full in the Audio-vision sequence 'Crustal patterns'.

** Defined in full in the Audio-vision sequence 'The origin of rocks' (associated with Unit 4).

TABLE 2

	Topography[1]	Age of Rocks[2]	Seismic activity (including depth of foci)	Volcanic activity (including whether effusive or explosive)
Continental features Cratons*				
Young mountain belts not bordering oceans				
Young mountain belts bordering oceans				
Oceanic features Ocean-basin floors				
Ocean ridges				
Ocean trenches			[3]	[3]

Notes

[1] Give approximate elevations relative to sea-level or another datum, such as ocean-basin floor, and state whether relatively rugged or smooth.

[2] Give age ranges, and describe their distribution patterns where appropriate.

[3] Include activity observed on adjacent continental crust.

* Defined in Figure 7 and the Audio-vision sequence 'Crustal patterns'.

SAQ 5 (*Objective* (*d*)) Complete Table 3 to describe the major distribution patterns shown by the phenomena discussed in the previous Sections. You should briefly describe their geographical distribution around the globe, and include comments on other patterns such as symmetry, or absence of a feature (in a particular region, or from continental or oceanic crust).

TABLE 3

	Geographical distribution[1]	Patterns/ associations[2]	Regions where absent or rare
Rocks older than 1 000 Ma			
Rocks younger than 100 Ma			
Effusive volcanic activity			
Explosive volcanic activity			
Zones of shallow earthquake foci			
Zones of intermediate and deep-focus earthquakes			

[1] Give a simple description, such as 'Circum-Pacific belt', 'along Mid-Atlantic Ridge', 'landward of ocean trenches', etc.

[2] In this column you should state whether one feature such as effusive volcanic activity, is found closely associated with another, such as a certain type of seismic activity. You should also comment on the relationship of age of rocks, volcanic and seismic activity to the major topographic features of the Earth.

2.5 Conclusion to Section 2

Perhaps you were surprised to find that all the data present on the *World Ocean Floor* chart, and in Figures 7–11, fitted into a pattern, with belts of volcanic and seismic activity running around the Pacific, stretching across Eurasia, and running down the centre of the Atlantic. Perhaps you were also surprised to learn that the rocks of the continents and oceans are vastly different both in terms of their age and the distribution pattern of the ages of rocks forming them. The data concerning the age of the oceans were only accumulated in the late 1960s and early 1970s, but most of the other information you have been studying was known to geologists for most of this century. So why did it take so long for a theory to emerge which could satisfactorily explain all the features we have discussed? And why did a theory like continental drift (first elaborated with a considerable amount of supporting geological evidence in 1915, as you will see) take so long to become widely accepted by geologists? These questions and the events which led to the revolution of plate tectonics are discussed in Section 3.

3 Before the revolution

Study comment This section gives an account of the events that led up to the formulation and acceptance of the plate tectonic theory by the geological community. We have used the names of individual scientists, and quoted from their original publications, to try to give you some impression of science as a human activity, rather than knowledge documented in textbooks. However, you are not expected to remember all these names. A chronological summary of key events in the development of plate tectonics is given at the end of Section 5. Allow about one hour for a first read through this section.

3.1 Introduction

Most practising geologists and historians of science agree that the work of a German meteorologist and polar explorer, Alfred Wegener, was 50 years before its time when first published in 1915. In this book, *The Origin of the Continents and Oceans*, Wegener discussed a variety of lines of evidence which he considered favoured the hypothesis of continental drift. In this Section, Wegener's ideas and evidence are summarized, and an account is given of the reactions of contemporary Earth scientists to them before World War II. But we first need to consider the climate of geological opinion in the late nineteenth century to see why Wegener was 'before his time'.

3.2 Before Wegener

In the nineteenth century, a number of scientists were so struck by the similarity of the shapes of the continents on either side of the Atlantic that they suggested theories to account for the phenomenon. In 1801 Von Humboldt suggested that the parallelism of shorelines could be accounted for by a vast flood carving a huge valley that is now the Atlantic. In 1858 Antonio Snider postulated that during the cooling period of the Earth the continents formed on one side only, this unstable situation being relieved during the Noarchian flood by the Old World and the Americas being pulled apart (see Figure 13). A similar pulling apart of a continental mass was suggested by the Rev. Ormond Fisher in 1881 to be the result of the birth of the Moon out of the Pacific, so that the light continental fragments would tend to float towards the newly created depression.

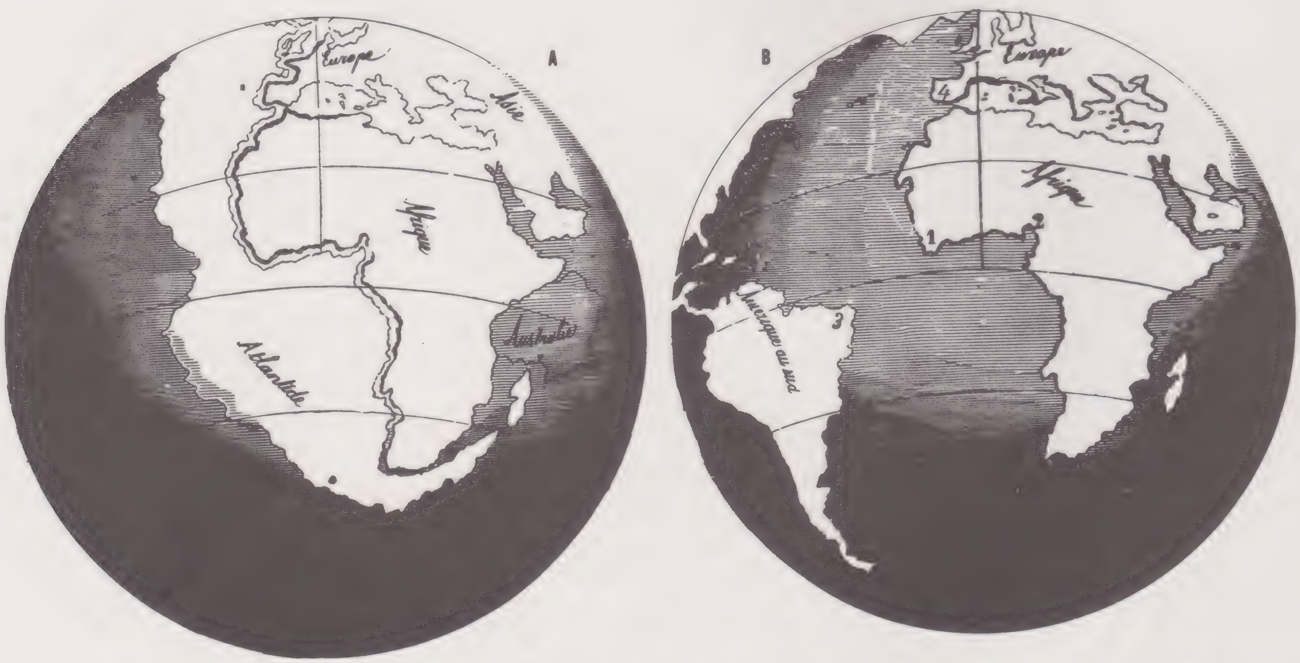


FIGURE 13 Snider's view of the Earth, published in 1858, showing the configuration of the continents during the period between Adam and Noah, and after separation which occurred during the Deluge.

The problem with all these ideas was that they had a *catastrophic* element in them; i.e. they involved unique events of tremendous proportions. Yet in the early part of the nineteenth century, geology had thrown off its biblical heritage, which involved floods and 'special creations', and adopted an approach that interpreted past events in terms of processes that can be observed on the Earth as it is today. Thus any hypothesis that smacked of catastrophism—as continental drift did around the turn of this century—was considered to be scientific heresy.

Quite apart from the fact that continental drift implied some kind of catastrophic process, it also contradicted another theory current in the late nineteenth and early twentieth centuries. At this time, the Earth was thought to be cooling down, and many scientists used this to calculate the age of the planet. Their estimates seldom reached 100 million years (compare this with current estimates, which are some 40 times this figure). Cooling implied a shrinking Earth, which, it was argued, resulted in the crinkling of the Earth's outer skin to produce mountain belts, much as an apple skin crinkles as the fruit inside dries out and contracts. But continental drift involved at the very least the possibility of crustal blocks moving around independently—an impossible feature to reconcile with a cooling, contracting Earth model in which the continents were pretty well fixed. With the discovery of radioactivity in 1896 (which is discussed in Radio 05) and its application to the dating of rocks which rapidly followed (discussed in Units 10, 11 and 26) estimates of the age of the Earth were considerably lengthened. But it takes time for such new ideas to become accepted by scientists—especially to those in unrelated disciplines. Thus it was many years after Wegener first formulated his ideas on continental drift that geologists in general came to realize the implications of radioactivity being an internal source of the Earth's heat.

3.3 Wegener and the origin of the continents: historical perspective

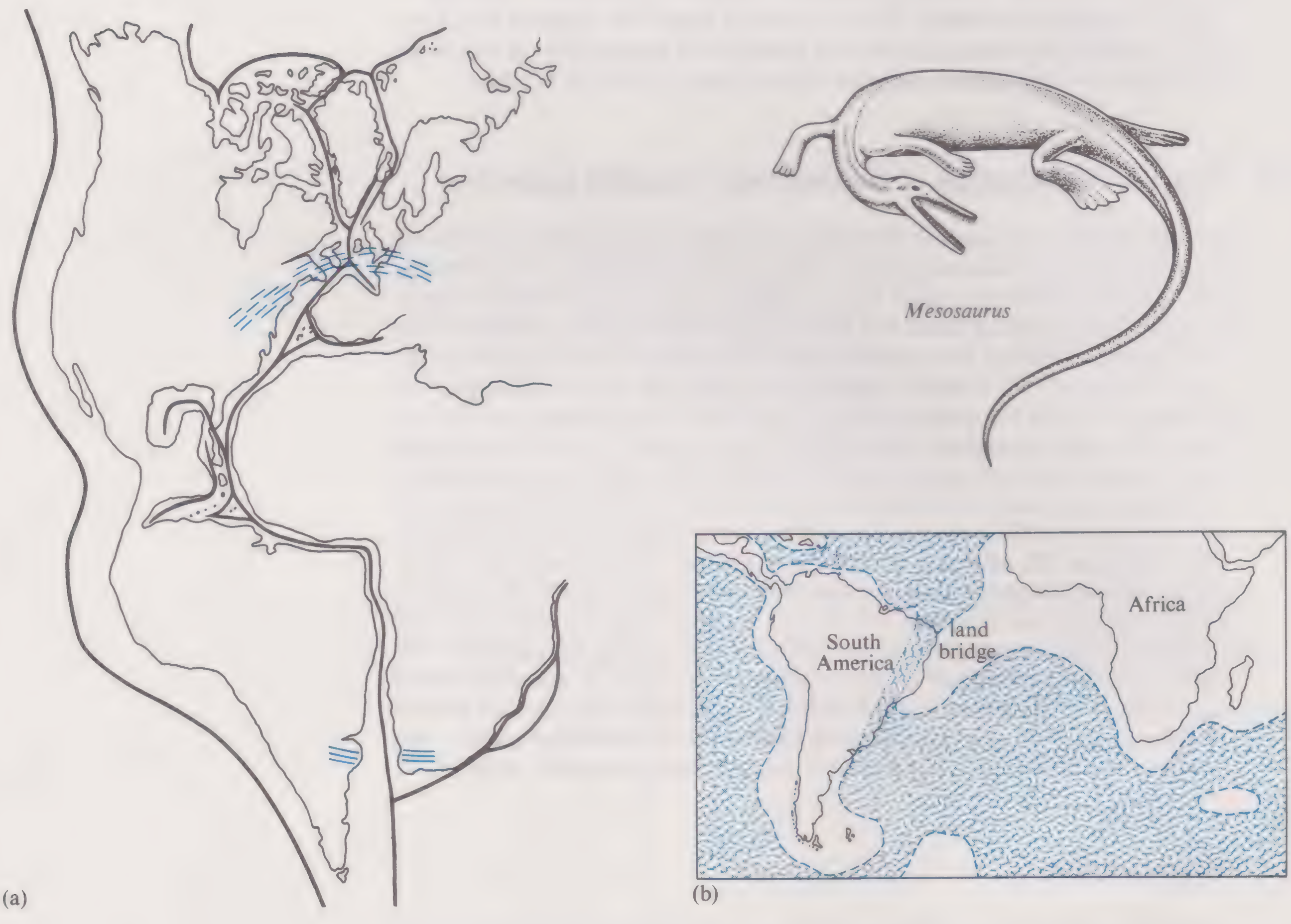
In 1910, Wegener first noticed the similarity between the opposing coastlines of the Atlantic when he was examining an atlas map. But it was only in the following year, when he accidentally came across a report summarizing the fossil evidence for a land-bridge uniting Brazil and Africa, that his ideas about continental drift really began to develop. Four months after this accidental discovery, he presented his hypothesis at two scientific meetings, after which he went to Greenland, returning in 1913. At the outbreak of the First World War, he joined the German army and served throughout the hostilities, but continued to elaborate his ideas on continental drift, and while on sick leave wrote his book, *Die Entstehung der Kontinente und Ozeane* (*The Origin of the Continents and Oceans*), which was first published in 1915. His work was little known in the English-speaking world until 1922, when the fifth edition of the book was reviewed in both Britain and America. In 1924 the English translation appeared (and is still in print!). The contents of *The Origin of the Continents and Oceans* are a testament to Wegener's wide interests, ranging across meteorology, palaeontology, geology and geophysics. He even conducted experiments on the origin of lunar craters by meteorite impact after seeing a bright meteor in 1916! Perhaps the breadth of his interests enabled Wegener to see links and patterns which had been overlooked by specialists—but in turn this enabled specialists to attack the drift theory on points of detail.

3.4 Wegener's case

The evidence presented by Wegener in favour of the continental drift hypothesis can be divided into several groups: continental fit, records of past climatic changes (including glaciation), crustal structure, direct measurement of increasing distances between continents, and the present-day distribution of land plants and animals. The last category will not be discussed here, because it involves detailed biological knowledge beyond the scope of the Course, and because it is regarded as suspect in the light of modern knowledge. Similarly, Wegener's reports of actual measurements of the increasing distance between continents over a number of years are now known not to be reliable (indeed, it is only in the last decade that reliable methods of measurement have been devised). However, a considerable proportion of Wegener's evidence concerned with continental fit, climatic change and crustal structure, has stood the test of time, and is worth considering in more detail.

Wegener did not place heavy emphasis on the fit of the shapes of the coastlines on opposing sides of the Atlantic (see *World Ocean Floor* chart). Instead, he cited evidence to suggest that continental masses, at present separated, *must* have been united in past geological times. Thus the pattern of mountain belts, and the distribution of fossils and rocks indicative of past climates all made more sense if continental drift had occurred (see Figure 14). Critics of Wegener argued that links between fossil communities could be accounted for by land-bridges (Figure 14b), or that mountain belts were once continuous across regions now covered by ocean (Figure 14a). Such explanations implied that continental crust could be changed in some way to oceanic crust. But Wegener proposed that the crust beneath oceans was fundamentally different from that beneath continents, and therefore argued that there was no way in which continent could be converted to ocean by vertical movements (or any other process).

FIGURE 14 Some of Wegener's geological evidence for continental drift.

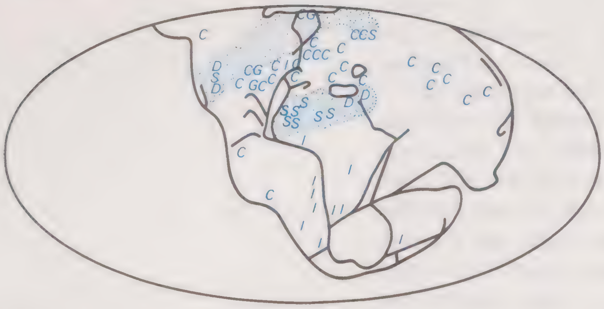


(a) Wegener's Atlantic continent reconstruction, published in 1915. Old mountain ranges (the ages of these were not known accurately in Wegener's time; they are now known to be up to 600 Ma old in North America and Europe, and about 200 Ma in the southern continents) are shown in blue and form continuous belts when the continents are fitted together. Note that Wegener has not fitted coastlines, but the rough positions of continental margins.

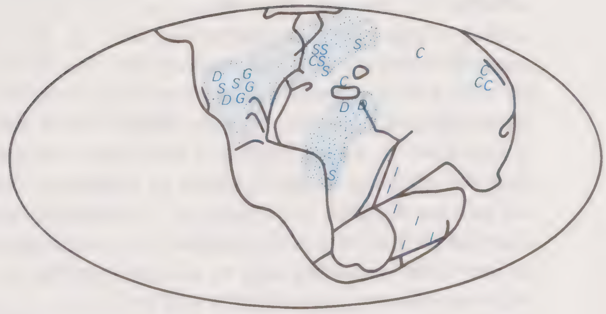
(b) Wegener argued that the distribution of fossils of *Mesosaurus*, a small reptile that lived over 200 Ma ago in shallow brackish (a mixture of salt and freshwater) waters in South America and Africa, could be best explained by involving continental drift. The 'conventional' explanation was that a 'land-bridge' connected the two continents and that this later subsided beneath the Atlantic Ocean.

FIGURE 14 is continued on the opposite page.

FIGURE 14 continued.



(c) 300 million years ago



(d) 250 million years ago

(c) and (d) Wegener's maps showing climatic belts as they might have existed 300 and 250 Ma ago.

Key

I Ice

D Desert sandstone

S Salt

G Gypsum

C Coal

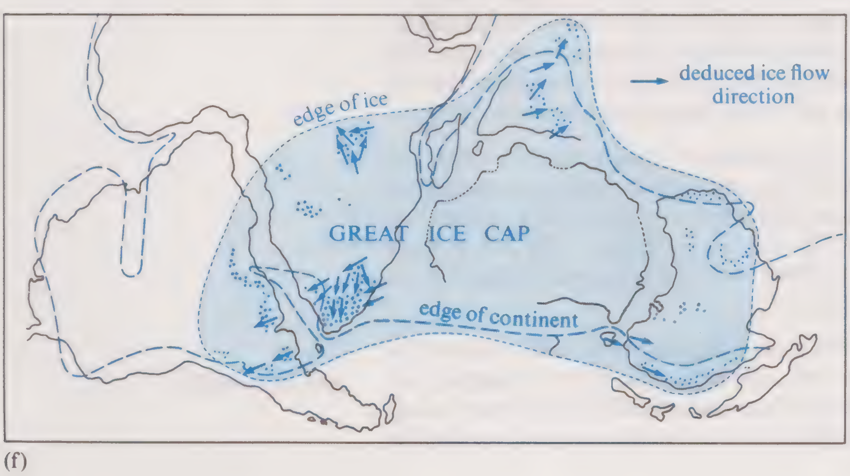
Stippled areas indicate arid zones.

These 'fossil climatic indicators' are discussed in TV 06. Such interpretations have been refined since Wegener's time, but more modern work has not altered his conclusions.

Desert sandstone, salt and gypsum form in hot, dry regions of the world today. Salt and gypsum are minerals that precipitate from seawater when it is evaporated. Coal is considered to form from the accumulation of plant material that grew in very wet, hot conditions, such as those in present-day equatorial regions. Note how, on Wegener's reconstructions, the occurrences of coal are on the Equator, and indications of hot, dry conditions flank this area to the north and south, just as African equatorial forests are flanked today by the Sahara and Kalahari Deserts. These maps show that 250 Ma ago, Europe, including Britain, was on the Equator (at which time, the coal in our coalfields was laid down) and 50 Ma later, Europe had moved north to become a desert region (some of the gas fields in the North Sea are found in 'desert sandstones' of this age).

(e)

Without invoking continental drift, the south polar ice cap shown in Wegener's reconstruction of the world 300 Ma ago (e) covered a huge area of the globe, and extended north of the Equator. Note that when the continents are reassembled in their pre-continental drift position (f), deduced ice-flow directions radiate away from a point in central southern Africa, providing yet more evidence in favour of a south polar ice-cap. This ice-cap probably formed in a highland region in the centre of a huge southern continent termed 'Gondwanaland' by geologists. There was probably no thick northern polar ice-cap, as this region was largely ocean 300 Ma ago.



(f)

Wegener largely based his belief that the oceans and continents were fundamentally different on the fact that 'there are two preferential levels for the world's surface which occur in alternation side by side and are represented by the continents and ocean floors, respectively'. He went on to state that 'it is therefore surprising that scarcely anyone has tried to explain this', and suggested that if elevations and depressions on the Earth's crust were due to uplift or subsidence of one level (as would happen if continents changed to oceans, and vice versa) then the resulting frequency curve of elevations would have only one peak and not two (as depicted in Figure 5, p. 12). Wegener suggested that the fact that the distribution had two peaks implied 'two undisturbed primal levels, and it seems an inevitable deduction that we are dealing with two different layers in the crust when we refer to the continents and the oceans. To put it in a rather picturesque term, the two layers behave like open water and large ice floes'.

The ice–water model implies that the surface features of the Earth are matched by larger irregularities on the lower surface of the crust (see Unit 4, Figure 41), and this state of equilibrium is described by the word *isostasy* (=equal standing). Another simple isostasy model is a piece of wood floating in water (see also the Home Experiment Notes for Unit 4). You could easily set up this model at home. If you float a piece of wood on water it will always float with the same volume below the surface. It is in a state of *isostatic equilibrium* or isostatic balance (Figure 15a). If you push the wood down, it will stay down only so long as you keep applying the force—the block is now in a new equilibrium state (Figure 15b). There is an additional upthrust from the extra water displaced that matches the downward 'push' on the woodblock. If you stop pushing, it will regain its original position and, in doing so, become isostatically readjusted. Land masses appear to behave just like that piece of wood. If they are displaced from their position of balance by some force they achieve a new state of balance but, once that force ceases to operate, isostatic readjustment takes place until isostatic equilibrium is regained once more. One great difference between the Earth and our wood-in-water analogy is the *rate of adjustment*. The wood takes fractions of a second to readjust to its equilibrium position, but land masses can be depressed or elevated several kilometres and their rate of readjustment is usually only a *few centimetres a year*. So a better analogy might be a brick resting on tar; the latter is so viscous that it would take days for the brick to sink into it.

isostasy

FIGURE 15 Woodblock and water analogy. (a) The block floats freely in water; (b) The block is depressed in water by an external force. See text for further discussion.

A vast quantity of evidence accumulated over the last century shows that isostatic equilibrium is the natural state of the Earth's surface and that isostatic readjustment takes place continually (due to the removal of crustal material by geological processes of weathering and erosion, or the melting of ice caps, to name but two examples). Many Earth scientists consider that the evidence is so strong that the term *law* is applicable to the process, *the law of isostatic readjustment.*

Can we qualify the picture we have just presented by measuring how much any part of the Earth is out of equilibrium? Yes, we can. It is done by measuring the regional variation of g, the gravitational attraction over the Earth's surface. You should recall from Unit 3 (Section 5.2) and Unit 4 (Section 1.2) that g varies systematically from the Equator to the Poles because the shape of the Earth is not a perfect sphere (it is an oblate spheroid).

In many places, however, it is found that g departs from what it should be according to calculation. Such departures are known as *gravity anomalies*, and many of them are due to the occurrence of excesses or deficiencies of mass caused by the crust being out of isostatic equilibrium. We shall discuss gravity anomalies again in Section 4.4.

gravity anomalies

Wegener cited evidence for isostatic readjustment from Scandinavia, where accurate measurements show that the region is rising by as much as $1\,\mathrm{cm\,yr^{-1}}$ (that is, one metre per century). This rise is considered to be the result of the melting of a thick ice cap that once covered the area, and which melted away over 10 000 years ago. But the crust is still adjusting to the release of the ice load, and will continue to do so for a considerable time.

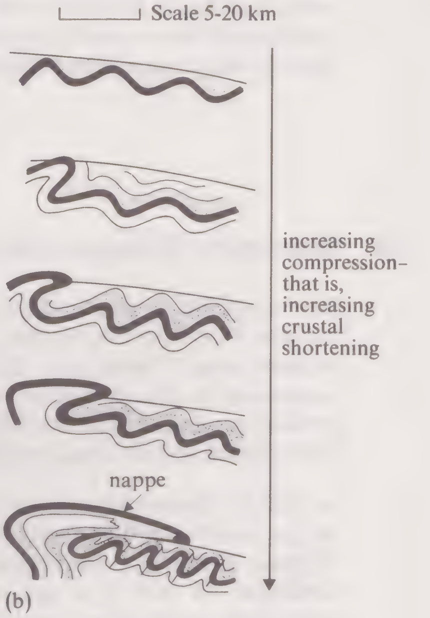
Wegener wrote:

> Isostasy theory depends on the idea that the crustal underlayer has a certain degree of fluidity. If this is so and the continental blocks really do float on a fluid, even though a very viscous one, there is clearly no reason why their movement should only occur vertically and not also horizontally, provided only that there are forces in existence which tend to displace continents, and that these forces last for geological epochs.

Wegener felt sure that there must be such forces because the effects of earth movements, compressing the crust, could be observed from the folding of rocks seen in mountain belts (see Figure 16).

FIGURE 16 Compression of the Earth's crust crumples rocks that were originally horizontally layered to produce these folds, seen in the cliffs of North Devon (a). These folds were produced during a mountain building period that occurred approximately 250 Ma ago. They provide evidence that the crust in the region was shortened by such movements. In areas such as the Alps and Scottish Highlands, fold structures termed nappes are found, indicating even greater crustal shortening (b).


(a)



(b)

3.5 Mechanisms for continental drift

At the beginning of Chapter 9 of his book, entitled 'The displacive forces', Wegener summarizes a situation which has applied to the development of many hypotheses and theories in science:

> The determination and proof of relative continental displacements, as shown by the previous chapters, have proceeded purely empirically, that is, by means of the totality of geodetic*, geophysical, geological, biological and palaeoclimatic data, but without making any assumptions about the origin of these processes. This is the inductive method**, one which the natural sciences are forced to employ in the vast majority of cases. The formulation of the laws of falling bodies and of the planetary orbits was first determined purely inductively, by observation; only then did Newton appear and show how to derive these laws deductively** from the one formula of universal gravitation. This is the normal scientific procedure, repeated time and again.

* Geodesy is the science concerned with the measurement of the size and shape of the Earth.

** See Unit 1 for definitions of these terms.

The Newton of drift theory has not yet appeared. His absence need cause no anxiety; the theory is still young and still often treated with suspicion. In the long run, one cannot blame a theoretician for hesitating to spend time and trouble on explaining a law about whose validity no unanimity prevails. It is probable, at any rate, that the complete solution of the problem of the driving forces will still be a long time coming, for it means the unravelling of a whole tangle of interdependent phenomena, where it is often hard to distinguish what is cause and what is effect.

As we shall see later, although geologists are confident that they have found a source of energy to 'drive' continental drift, the exact nature of the movements within the Earth are still not clear. So it is small wonder that Wegener discussed a variety of possible causes, none of which—unlike the drift theory itself—have stood the test of time. He suggested that drift might be 'powered' by the *Pohlflucht* (flight from the Poles) force, a differential gravitational force caused by the fact that the Earth is not a perfect sphere, having a polar radius some 21 km smaller than its equatorial radius (see Unit 4, Figure 1). Thus the value of g is slightly lower at the Equator than at the Poles, and so might, over long periods of time, be sufficient to cause continental drift. Another force suggested was that of tidal friction: just as the Sun and Moon cause tides in the oceans, so they might in the crust, resulting in a westerly drift. But the *Pohlflucht*, though it does exist, is now known to be far too small to cause drift, and if the tidal friction effect *had* worked, then the Earth would have stopped rotating in a matter of days.

3.6 Reaction to Wegener: stabilists versus mobilists

It is impossible to give an accurate indication of how the scientific community reacts to a new idea even during the time when the debate is actually taking place, let alone some 50 years later. But scientists' habits of organizing and attending conferences to present and discuss new ideas, and then to publish conference proceedings, ensures that the main elements of past controversies, and the postures adopted by individual researchers, are documented for posterity.

In 1922, the British Association for the Advancement of Science held a discussion on the continental drift hypothesis, and in 1926 a similar symposium, at which Wegener was present, was organized by the American Association of Petroleum Geologists. At both these gatherings the reaction to continental drift was overwhelmingly hostile, even sarcastic. One participant even went so far as to state that if drift were to be accepted, virtually all the previous results of geological researches would have to be abandoned. Wegener's continental fits were criticized, largely because he had never discussed them in detail, and apparently had not allowed for the fact that uplift and subsidence at continental margins might have distorted such outlines. His postulation of the existence 300 Ma ago of a single huge south polar ice sheet (see Figures 14e and 14f) was doubted by some on the grounds that it was sited in the interior of a huge continent, and so would not have received heavy snow falls brought in by moist winds blowing over a nearby ocean. These critics thought this huge continent, if it had existed, would have experienced conditions much like those in Siberia today—very cold, but relatively dry. Palaeontologists questioned Wegener's conclusion that similarities between the distribution of fossil plants and animals on now-separated continents *must* imply that drift had occurred between them. They argued that alternative methods of migration, via a few land-bridges, or by island-hopping or even on rafts (see Figure 17 for a more recent view of such ideas) were quite adequate to cause the observed similarities. Wegener's claim that the rate of drift could actually be measured was not accepted, for the simple reason that the majority view was that no means existed whereby such measurements could be made.

The strongest critics of the continental drift hypothesis were geophysicists, most notable among them Harold Jeffreys of Cambridge University. He and many others believed that the properties of the outer part of the Earth were such that

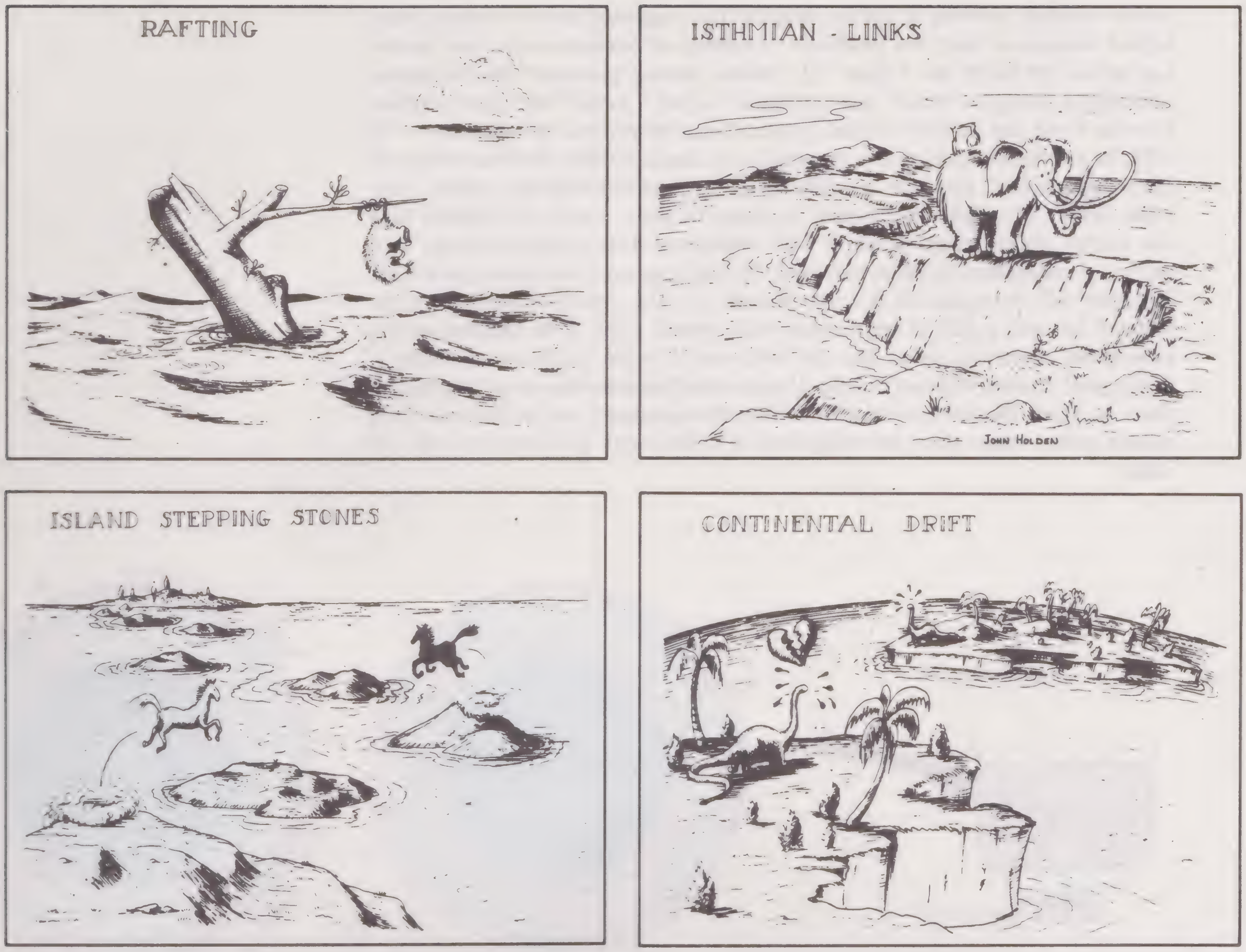
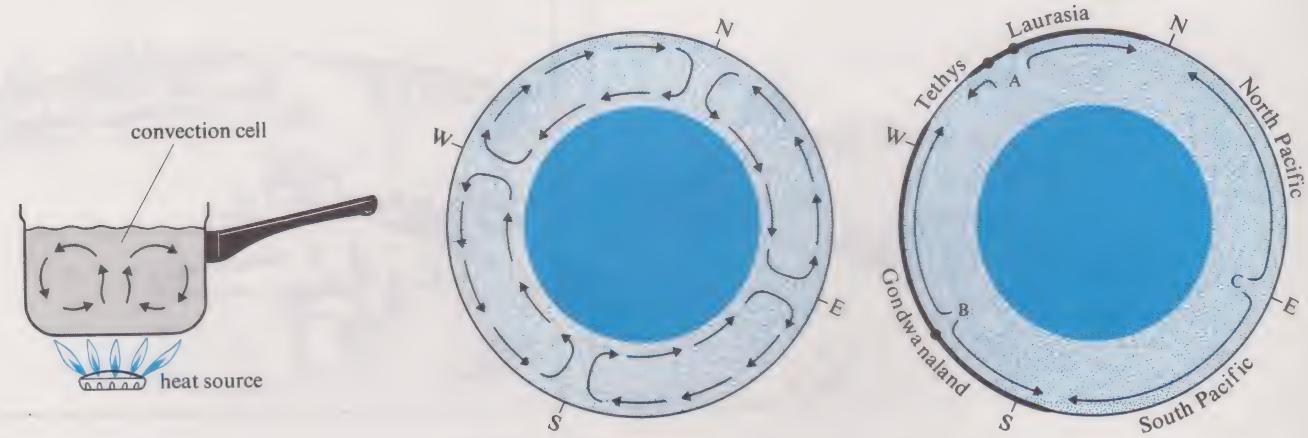


FIGURE 17 An illustration of alternative methods whereby organisms could have migrated between continents. Wegener argued that the distribution of fossil organisms favoured his drift hypothesis, but most palaeontologists at the time favoured a combination of the other processes.

there was no way the continents could be envisaged as ploughing through the crust, and even if there was a force strong enough to drive them, why was it that only some of their edges were crumpled during drift? Without an acceptable 'driving force', drift theory held little attraction for the majority of geologists, brought up on a diet of vertical crustal movements which appeared quite adequate to explain the Earth's surface features and its history. So geologists continued their work much as before, for despite the discovery of radioactivity, which provided an internal source of heat, the concept of a contracting Earth still held sway. The discovery of radioactivity may have lengthened geologists' concept of Earth history, but apparently it had broadened few minds.

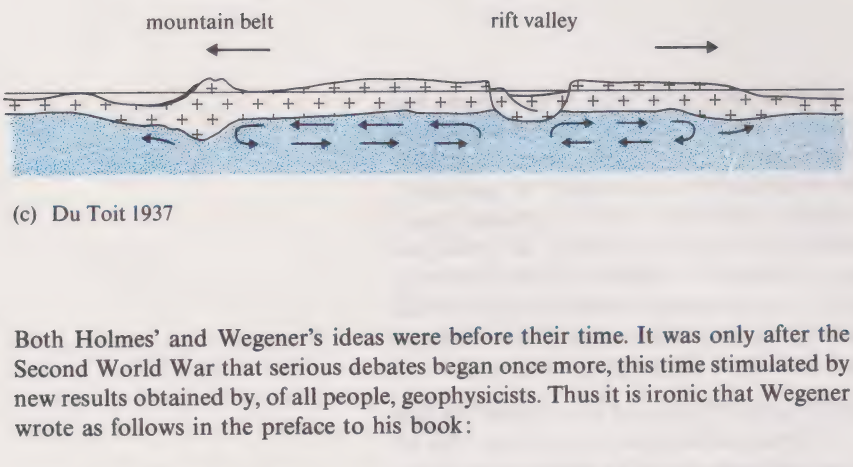
But there were geologists who favoured Wegener's ideas, and to an extent this was related to where they worked. Some who had studied the structure of the Alps, or older mountain belts such as that in Scotland were struck by the fact that major *horizontal* movements had to be inferred from their results (see Figure 16), and continental drift explained the cause of such movements. Similarly, several Dutch geologists working in the East Indies area of the Pacific, with its frequent earthquakes and volcanic activity, and numerous oceanic trenches, found Wegener's ideas more attractive than the conventional 'stabilist' view. Wegener's most ardent disciple, a South African named Alexander Du Toit, was clearly influenced by his knowledge of the geology of the southern continents, where the evidence for drift is recognized today as being the least equivocal.

Arthur Holmes, working in Britain, and Du Toit suggested that the driving force behind continental drift was produced by systems of convection currents operating within the Earth (see Figure 18). Holmes, having pioneered the systematic radioactive dating of rocks*, was concerned to find a model that would explain how the Earth lost its internal heat generated as a by-product of radioactivity. In 1931, he published a paper, now regarded as a classic, entitled 'Radioactivity and Earth movements', and later he elaborated his ideas in his classic geology textbook (1944), *Principles of Physical Geology*. In these works, he showed how the Earth's major surface features and continental drift could be related to a system of convection currents 'powered' by heat produced by radioactivity (radioactivity will be explained in Units 10 and 11). The upwelling currents, when situated beneath a slab of continental crust, would result in its separation and subsequent migration, much like the behaviour of scum on the top of a pan of boiling jam. Unlike Wegener's model of continents being analogous to floating ice-floes on water, Holmes' model moved both the continents and some underlying denser crust, rather than assuming that the continents ploughed through the crust.



(a)

(b) Holmes 1931



(c) Du Toit 1937

FIGURE 18 Convection currents and continental drift.

(a) An analogy: in the kitchen, a saucepan of soup or jam simmers, and a system of convection currents is established. Heat from the gas ring enters the system at the base of the pan, and is carried upward by the less dense, hotter liquid. Heat is lost at the surface, and so the cooler, denser liquid sinks. In the Earth, the heat source is from radioactive materials in the crust and mantle.

(b) Holmes' hypothesis, published in 1931, shows an idealized convection system within the mantle, and an interpretation of the convection system that might have broken up the southern continent of Gondwanaland (South America, Africa, India, Australia and Antarctica) and the northern continent of Laurasia (North America, Europe, Asia) over 100 Ma ago. The Tethys was a large ocean, the only part of it remaining today being the Mediterranean.

(c) Du Toit's hypothesis, published in 1937, shows a very flat convection system postulated to be rising under rift valleys (See Figure 32b, p. 46).

Both Holmes' and Wegener's ideas were before their time. It was only after the Second World War that serious debates began once more, this time stimulated by new results obtained by, of all people, geophysicists. Thus it is ironic that Wegener wrote as follows in the preface to his book:

> I myself in a weak moment once wrote of the drift theory: 'I believe that the final resolution of the problem can only come from *geophysics*, since only that branch of science provides sufficiently precise methods. Were geophysics to come to the conclusion that the drift theory is wrong, the theory would have to be abandoned by the systematic earth science as well, in spite of all corroboration, and another explanation for the facts would have to be sought'.

* This technique will be explained in Unit 26.

3.7 Objective of Section 3

Now that you have finished Section 3, you should be able to achieve the following Objective:

(a) Correctly list or recognize from given examples, the major lines of evidence that you have studied so far that support the continental drift hypothesis.

Now test yourself by completing SAQ 6.

SAQ 6 (*Objective* (*a*)) List the four major lines of evidence that support the continental drift hypothesis.

4 Plate tectonics: the revolution

Study comment Although references to individual scientists, and dates of particular advances, are given in the succeeding sections, you are not expected to recall these in detail. However, you should recall the general sequence of events: first how palaeomagnetic evidence made geophysicists reconsider their view that continental drift was a physical impossibility, and later how Harry Hess's views on the origin of ocean basins provided a major stimulus to the interpretation of a variety of data. You should also realize that military interests played a major part in sponsoring the exploration of the oceans.

The historical thread of this account connects descriptions of a considerable amount of data that support the theories of continental drift and sea-floor spreading. You should already be able to describe the continental drift hypothesis; after you have finished Section 4 you should also be able to describe the sea-floor spreading hypothesis, and, even more important, be able to document the evidence supporting both these hypotheses.

Allow two to three hours for your first reading of this Section.

4.1 New evidence, new inspiration

The continental drift debate flared up once more in the 1960s, once new evidence from both the continents and oceans had been accumulated. Many of these data were obtained through the use of new technologies, such as palaeomagnetic methods (see Unit 5) and much more 'routine' and precise methods of dating rocks. For the first time the ocean floors were systematically surveyed by research vessels, using equipment that owed much of its development to the stimulus of the Second World War, such as magnetometers and echo-sounders (for mine and submarine detection). This military influence also affected the funding of research, for a good deal of the American effort in ocean exploration was paid for by the Office for Naval Research, which, of course, had a strong interest in a better knowledge of the oceans, because of the developments in submarine warfare that took place in the 1950s and 1960s. Even the Cold War played a part in stimulating the development of new technologies to drill beneath the ocean floor, for rumours (eventually shown to be unfounded) that the Russians might be planning to drill down to the Mohorovičić discontinuity helped stimulate the allocation of funds to the American 'Mohole' Project. The American attempt to drill to the Moho was abandoned in 1966, partly because of the technical difficulties involved, partly because of cost and partly due to political intrigue. But out of it was born the Deep-Sea Drilling Project, which has now become an international research programme with five nations participating.

The following Sections deal in turn with each category of evidence that led to the formulation of the plate tectonic theory. As far as possible, they are arranged in historical order. However, bear in mind that developments in one research field were very often taking place at the same time as those in another.

By the end of the 1950s the new data stimulated the presentation of a new hypothesis for the origin of the ocean basins which was then tested during the 1960s.

4.2 Polar wandering: the geophysicists recant

From the mid 1950s onwards the results of palaeomagnetic studies (described in detail in Unit 5), conducted at the University of Cambridge and Imperial College, London, yielded evidence that forced geophysicists to reconsider continental drift

as a possibility, despite their reservations that the physical properties of the Earth's crust seemed to make it impossible. Determinations of apparent palaeopole positions over the past 500 Ma of geological history showed that the position of the magnetic poles had apparently drifted considerably during this time. Such plots of palaeopole positions through time are made in just the same way as that shown in Figure 21 of Unit 5. Observations from rocks of the same age from the same continent are found to be clustered together, and so the average of the readings gives the palaeopole position. A line connecting successive palaeopole positions is known as a polar wandering curve. As the Earth's magnetic field is considered always to have been a dipole field which, over a period of time, coincides with the Earth's axis of rotation, such curves either imply migration of the continents through latitudes, or a shift in the position of the Earth's rotational axis. Wandering of the geographic poles, that is a change in the position of the axis of the Earth's rotation, was considered possible, but this would produce magnetic polar wandering curves that are the same for each continent. *But the data showed that the polar wandering curves from different continents* (which are drawn *without* assuming that drift has occurred) *could only be reconciled by invoking continental drift* (see Figure 19 and TV 06).

polar wandering curves

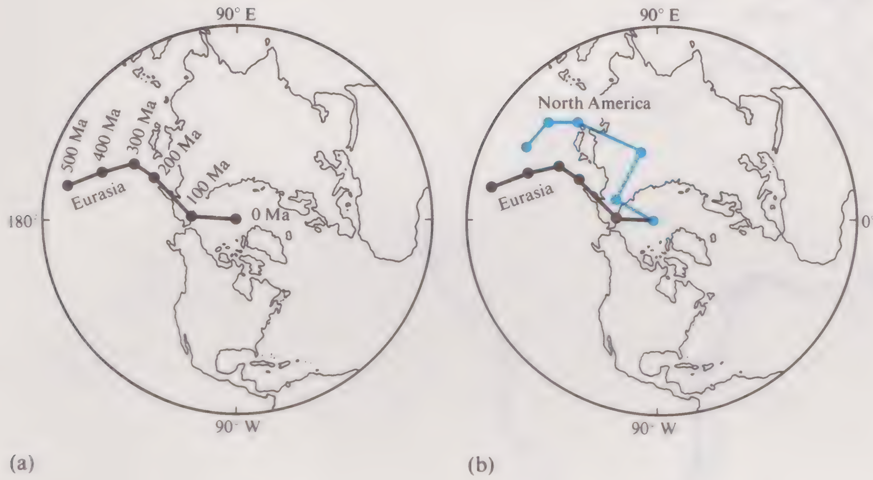


FIGURE 19 Polar wandering curves for Europe and North America, with the present North Pole shown in the centre of each map.

(a) The curve for Europe shows a steady shift of the palaeopole position (as measured with reference to the present location of Europe) from near the Equator towards the present North Pole. This observation can either be interpreted as being due to the latitudinal migration of Europe through time, or being caused by changes in the position of the Earth's rotational axis. A single curve such as this is *not* evidence in favour of continental drift.

(b) When the curve for North America is added, a similar northward shift is revealed, but the curve is not the same shape. The main difference occurs between 200 and 100 Ma ago, suggesting that the two continents drifted apart during this period. The difference between these two polar wandering curves can *only* be reconciled by invoking continental drift.

Remember that polar wandering curves indicate movement only in a relative north–south sense, and provide no information about the longitudinal position of continents in the past. Nonetheless, they can be used to aid reconstructions of past fits of slabs of continental crust.

4.3 Ocean bathymetry* and continental fits

The stimulus given by the results of palaeomagnetic studies forced geophysicists to reconsider the possibility that continental drift had occurred. This led Professor Sir Edward Bullard and some of his colleagues at the University of Cambridge to examine the question of the 'fit' of continents in a more objective way than had been done hitherto. They produced a map (Figure 20a) that showed that continents bordering the Atlantic could be fitted along the 500 fathom (1 000 metre) contour with overlaps and gaps of less than 90 km. This reconstruction was not very different from those proposed by many earlier workers, including Wegener, yet is today almost universally accepted and used by geologists—perhaps it has proved more acceptable because it was not drawn by a scientist, but by a computer! But the computer was programmed to produce a best 'fit' of continental margins to minimize the number of gaps and overlaps.

(a)

FIGURE 20 Piecing together the continental jigsaw. Evidence that continents now separated by thousands of kilometres of ocean were once joined can be obtained by (a) fitting them together on the basis of their underwater topography, or *bathymetry*; (b) by matching the geographic distribution of rocks of various ages; and (c) by comparing sequences of rocks and their contained fossils on either side of oceans.

(a) The fit of the Atlantic continents at the 500 fathom (1 000 metre) contour. Solid colour indicates overlaps; stipple indicates gaps. Some of the overlaps can be accounted for by features that have 'grown' since the Atlantic opened (for example, the Niger Delta and the area off Florida). Note that Iceland is left out of the reconstruction for this reason; it is a pile of volcanic rock that has accumulated since the Atlantic began to open.

* The measurement of water depth.

Following the publication of the Bullard map, geologists were able to match up the distribution of rock provinces defined on the basis of their ages (determined by radioactive dating methods) on either side of the Atlantic and found that the patterns on the 'jigsaw' pieces (that is the ages of rocks on opposing continents) fitted together beautifully (Figure 20b). They also found that younger rocks (less than 140 Ma old) interpreted to have formed in freshwater conditions and later in marine conditions were remarkably similar on either side of the Atlantic (see Figure 20c). Such detailed comparisons not only support the hypothesis that Africa and South America were once juxtaposed (because the cratons could be pieced together, and because sediments around 130 Ma old contained the same species of *freshwater* fish), but also give a clue about when drift began (marked by the occurrence of salt evaporated from seawater which occupied a narrow gulf between the newly opened continents).

rocks older than 2000 Ma

rocks formed between 600 and 2000 Ma

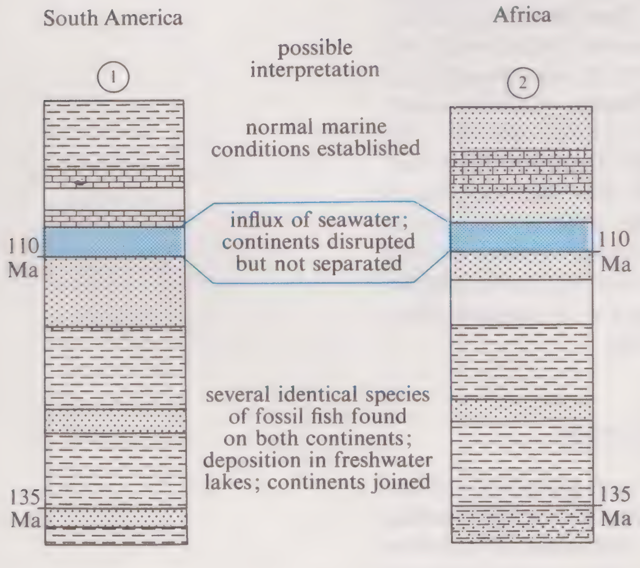
(b)

rocks deposited 100 – 140 Ma ago

1 2 see Figure 20c

FIGURE 20

(b) The fit of South America and Africa. The main cratonic areas can be matched on either side of the Atlantic, and in addition, the small areas along the Atlantic coasts of the two continents contain very similar sequences of sedimentary rocks: examples of which are shown in (c).



shale

sandstone

(c) limestone

salt

FIGURE 20

(c) The freshwater sediments on both sides of the Atlantic contain similar fossil fish, and so must have been formed close to one another. The sequence of sediments also contains a record of the first stages of the opening of the Atlantic, with salt deposits being formed by evaporation from a narrow seaway which opened when the two continents were first separated.

Thus both the bathymetry and the geology of continental margins bordering the Atlantic provide strong evidence for the drift theory. But the shape of the ocean floors, which for so long defied explanation in terms of land-based geology, is also significant for the drift theory. The existence of the Mid-Atlantic Ridge was known in the late nineteenth century, as a result of surveys conducted by cable-laying ships, but Pacific Ocean ridges were only discovered in the 1950s. Similarly, the axial rift zone of the ridges and the incredible symmetry displayed by parts of them (see Figure 21) are relatively recent discoveries.

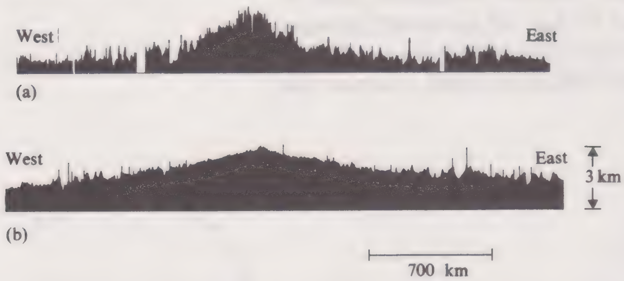


FIGURE 21 Topographic profile (a) across the mid-ocean ridge in the North Atlantic and (b) across an ocean ridge in the Pacific. Note the much more 'rugged' topography of the Atlantic ridge and its marked symmetrical (or mirror image across the central rift) appearance. The Pacific example shows a degree of symmetry, but it is much less than that for the Atlantic. The Mid-Atlantic Ridge develops a central rift valley that runs along its length (see the *World Ocean Floor* Chart): it is broadly comparable in topographic shape to continental rift valleys, such as the Rhine Rift Valley, and those in East Africa. The pattern of geological *faults* that produce these rifts is described in Figure 32 on page 46. Note that (a) contains three gaps due to the incomplete nature of the survey on which it is based.

But there is more to ocean basins than just ridges: look at the Pacific part of the *World Ocean Floor* chart. As well as the ocean ridges and flanking trenches, this region is characterized by numerous oceanic islands and submerged seamounts. Many of these seamounts have flat tops and are termed *guyots* (for example, Hess Guyot to the west of Hawaii at the SW end of the Necker Ridge). During the latter part of the Second World War Professor Harry Hess of Princeton University commanded a troop ship supporting landings in the western Pacific, and during such voyages he ordered the ship's echo-sounder to be left on continuously. The resultant data enabled him to identify a number of flat-topped submarine mountains up to 2 km beneath the surface of the oceans, but rising by as much as 4 000 m above the sea-floor. He named them *guyots* after the flat-topped geology building at Princeton, which was in turn named after Arnold Guyot, the first geology professor in the department. Hess thought these features to be ancient volcanoes, whose flat tops had been produced by erosion by the sea at sea-level, after which they had subsided slowly (see Figure 22). He also thought that they were fairly old, more than 600 Ma, but in 1956 sediments of *shallow-water* origin sampled from the tops of some mid-Pacific guyots were proved to be relatively young, dating at about 100 Ma before the present. These new data posed the problem: why had the guyots subsided so rapidly after their formation? Another fascinating feature concerning guyots was the discovery that some situated on the edges of ocean trenches are tilted like leaning Towers of Pisa, looking suspiciously as though they are riding a conveyor belt down into the trenches. As we shall see in Section 4.6, in 1960 Hess was to integrate these observations, and others, into an all-embracing hypothesis.

guyot

4.4 Ocean trenches, gravity anomalies and Benioff zones

Before the Second World War, the Dutch geophysicist Vening Meinesz had discovered that large *negative* gravity anomalies are associated with ocean trenches. Before discussing the significance of these anomalies, and some of the other features associated with trenches, we need to take up again the discussion of gravity anomalies we began in Section 3.4. Remember that we explained isostasy

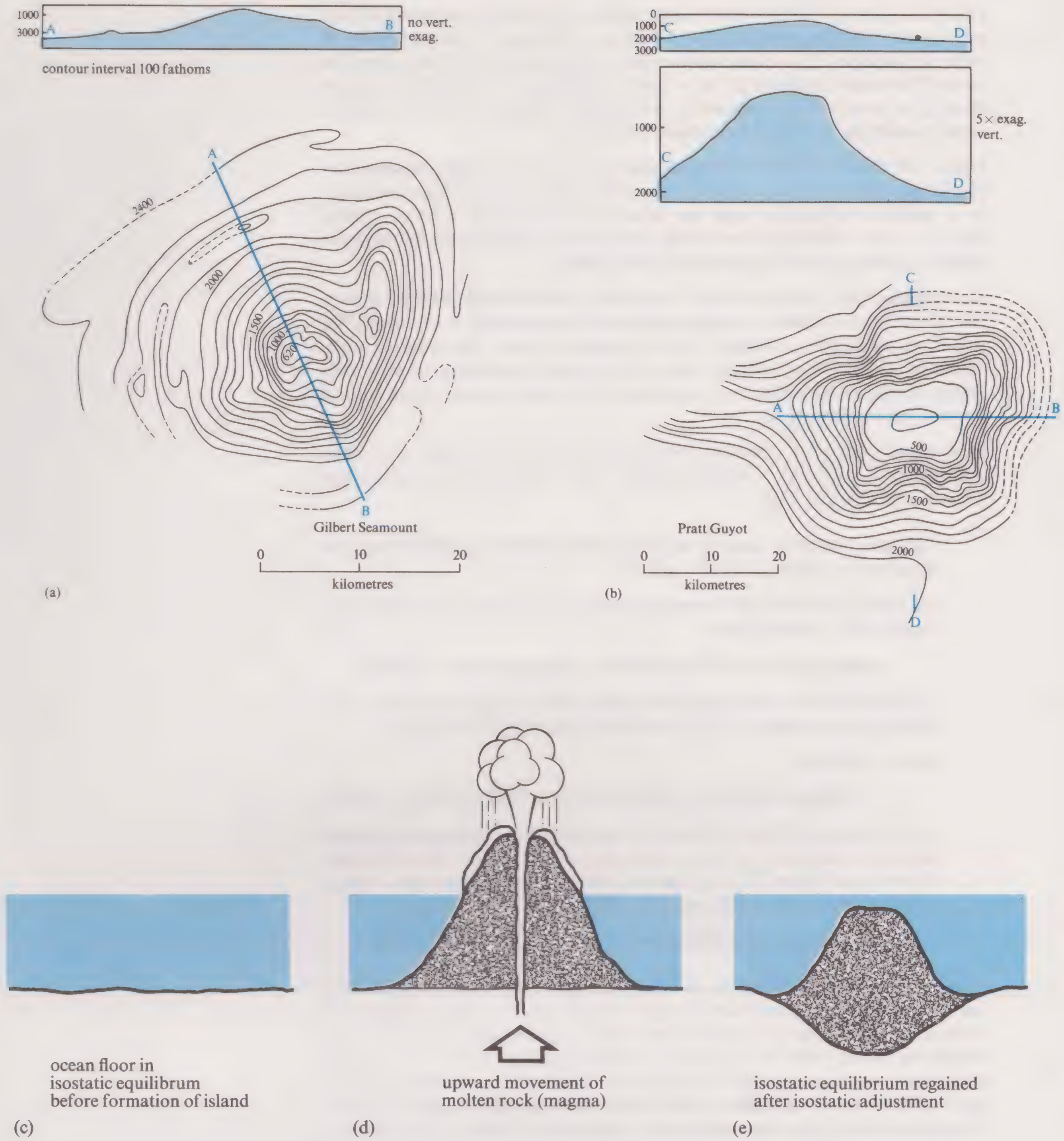


FIGURE 22 Seamounts, guyots and isostatic adjustment.

(a) Contour map and section of a seamount in the Newfoundland Seamount group.

(b) Contour map and sections of a flat-topped guyot situated south of the Canary Islands.

(c), (d) and (e) Sequence of events leading to the formation of seamounts and guyots. At stage (d), the build-up of the volcanic pile proceeds faster than the rate at which isostatic adjustment can compensate for the added mass, and so an island is formed. Once volcanic activity ceases, the island subsides beneath the sea due to isostatic adjustment, and erosion may plane the island flat to produce a guyot (e).

using the analogy of wood floating on water. Let's look at this analogy again, but this time from a quantitative viewpoint. What actually happens when you push the woodblock further down into the water?

Figure 23a shows a cube of wood floating in water. The cube has a volume of 1 m^3 and a mass of 500 kg (that is, it has a density of 500 kg m^{-3}). As the density of water is 1 000 kg m^{-3}, the block will float immersed to a depth of 0.5 m, so that the mass of the water displaced (0.5 m $\times$ 1 m^2 $\times$ 1 000 kg m^{-3} = 500 kg) is equal to the mass of the wood cube (remember Archimedes' principle, which you applied when completing the Home Experiment in Unit 4).

Figure 23b shows a new equilibrium position of the wood cube, produced by placing an additional mass of 250 kg on top of it. The cube now floats immersed to a depth of 0.75 m, for now the mass of the displaced water is 750 kg (0.75 m $\times$ 1 m^2 $\times$ 1 000 kg m^3 = 750 kg). This mass is, of course, equal to the mass of the woodblock plus the extra mass placed upon it.

Now imagine that the extra weight is suddenly removed from the cube (Figure 23c). Consider the situation an instant after this has happened: is the wood cube still in an equilibrium position? No, of course, it is not. The mass of water displaced is still 750 kg, but the mass of the floating wood cube is now only 500 kg. So the wood will start to move out of the water because there is a net upward force of 250 gN.

Now consider the mass of material (wood, plus water, or wood plus extra mass plus water) in a column of arbitrary depth, say 1.5 m, below the water surface (Figures 23d, 23e and 23f).

Calculate the total mass of material in the column in each of the three situations in Figures 23d, 23e and 23f.

In 23d it is the mass of the wood plus the mass of the 1 metre column of water (1 m^3 volume), that is:

mass of column = 500 kg (wood) + 1 000 kg (water) = 1 500 kg

In Figure 23e, it is the mass of the extra load plus the mass of the wood block, plus the mass of a 0.75 m column of water (0.75 m^3), that is:

mass of column

= 250 kg (extra load) + 500 kg (wood) + 750 kg (water) = 1 500 kg

So the masses in Figures 23d and 23e are exactly the same, and this would be true irrespective of what depth was chosen to do the calculation. However, in Figure 23f, at the instant before the wood cube begins to move upwards, the result is different:

mass of column = 500 kg (wood) + 750 kg (water) = 1 250 kg

In terms of the concept of isostasy discussed on page 24, the block in Figure 23f is *not* in isostatic equilibrium; there is a mass deficiency in this column compared to those shown in Figures 23d and 23e. Remember the brief explanation of how local variations of the value of g (gravity anomalies) can be used to detect mass deficiencies or excesses caused by the crust being out of isostatic equilibrium (p. 24). What kind of instrument could measure the mass of material in a column of arbitrary depth below the surface of the wood cubes in Figure 23, or below the surface of the Earth?

Remember from Unit 3 that there is a gravitational force of attraction between any two masses m_1 and m_2 separated by a distance d:

$$F = Gm_1m_2/d^2 \quad (1)$$

where G is the universal gravitational constant = $6.558 \times 10^{11}\ \mathrm{N\,m^2\,kg^{-2}}$.

Now Newton showed that the law of gravitation could be applied to calculate the force on an object of mass m at the Earth's surface as

$$F = GmM_E/R_E{}^2 \quad (2)$$

where M_E = mass of the Earth

R_E = radius of the Earth (assumed to be spherical)

Note that equation 2 says that the force on the mass m at the Earth's surface is the same as it would be if the entire mass M_E of the Earth were concentrated at its

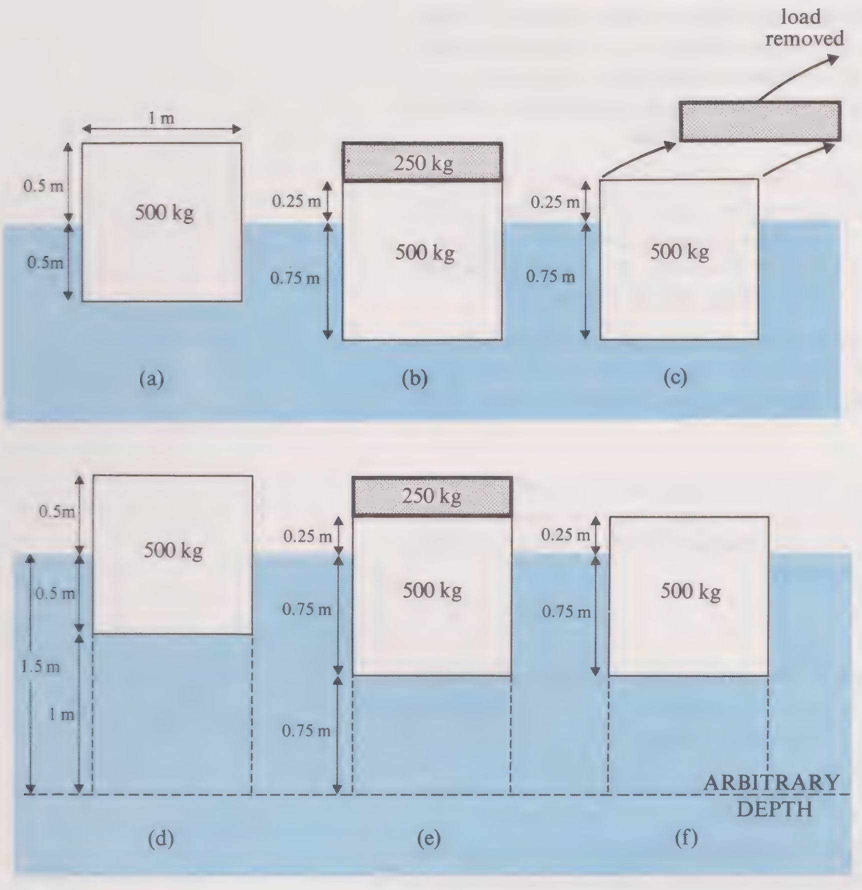


FIGURE 23 Woodblock and water analogy: further explanation. A wood cube of volume $1\,m^3$ is floating in water (a), and has an extra load of 250 kg placed on it (b). The load is then removed (c). For (d), (e) and (f) see discussion in the text.

centre. It is not by any means self-evident that this should be so. Indeed Newton had to develop an entirely new branch of mathematics* to prove that it was so. In fact equation 2 follows from equation 1 only if the Earth's mass is distributed symmetrically within the Earth's interior (that is, provided the mass per unit volume at any point inside the Earth depends only on the distance of that point from the centre.)

Assuming, for the moment, that this condition *is* fulfilled and that equation 2 applies to any point on the Earth's surface, and remembering that Newton's second law says that the acceleration g of a mass m acted on by a force F is:

$$F = mg \qquad (3)$$

then if F in equation 3 is the same as the gravitational force F in equation 2, we have

$$F = mg = GmM_E/R_E{}^2$$

therefore

$$g = GM_E/R_E{}^2$$

So an instrument that can measure the gravitational acceleration g would, on the assumption that we are making for the moment (that the Earth has spherical symmetry), read the same at every point on the Earth's surface. So the assumption of spherical symmetry amounts to saying that, in a column of small cross-section (say $1\,m^2$) extending all the way from the surface to the centre of the Earth, the mass of material in the column and the distribution of that mass over the depth of the column is *exactly the same* for every such column irrespective of whereabout on the Earth's surface it starts. But this is a gross oversimplification. Firstly on the global scale, because the Earth is *not* exactly spherical: it is flattened at the Poles (the polar radius is about 21 km less than the equatorial radius). So there will be more mass in a column starting at the Equator than in one starting from one of the Poles, but g will be lower at the Equator than at the Poles, since $g = GM_E/R_E{}^2$ and R is greater at the Equator. However, on the *local* scale, you have already

* He called it the 'method of fluxions'. Today, it is known as 'integral calculus'.

seen that the mass in a column of arbitrary depth depends upon whether the crust (the wood cube in Figure 23) at the top of the column is or is not in isostatic equilibrium, and that if it is *not*, an instrument measuring the mass in the column—by measuring g at the surface—will show a gravity anomaly, that is a value of g differing from the normal value for that latitude.

Consider the situations in Figures 23d, 23e and 23f: if the value of g were measured at points at the same heights across the models, would you expect the value of g to change across any of them (assuming the instrument used was sensitive enough to detect such small changes)? The value of g would remain the same across Figures 23d and 23e, but would change across Figure 23f.

Now consider a more realistic geological example: the formation of a volcanic island and its subsequent subsidence beneath the ocean due to isostatic adjustment (see Figure 22 on page 35). In this case the force acting on the crust is the build-up of a mass of volcanic rock.

ITQ 1 At which stage in Figure 22 (c, d or e) would you expect the value of g over the site of the volcanic island to depart from the normal value? And would it be higher or lower than the normal value (i.e. characterized by a *positive* or *negative* gravity anomaly)?

Answers to ITQs begin on p. 77.

You should now have a clearer picture of the significance of gravity anomalies. The unit used on gravity maps is the *milligal* (a thousandth of a *Gal* (named after Galileo) which is $1\,\text{cm}\,\text{s}^{-2}$). A milligal (abbreviated to *mgal*) is not an SI Unit: it is precisely defined as $10^{-3}\,\text{cm}\,\text{s}^{-2}$, which is $10^{-5}\,\text{N}\,\text{kg}^{-1}$. Recall from Unit 3 (Section 5.2) that g (the acceleration due to gravity) is about $9.81\,\text{N}\,\text{kg}^{-1}$, so a milligal is approximately one millionth the value of g. Thus instruments used to map gravity anomalies are extremely sensitive. Gravity maps are produced by drawing lines between points of equal departure from the value of g (allowing of course for the fact that this varies over the Earth's surface due to the fact that it is not a perfect sphere): These lines are analogous to topographic contours and are known as *isogals*.

Where there is no gravity anomaly, the isogal would have zero value (0 mgal). A positive anomaly (excess of mass) is given a plus sign (for example, +10 mgal for a small positive anomaly, or +100 mgal for a large one), and a negative anomaly (deficiency of mass) is recorded by a minus sign (for example, −10 mgal, small; −100 mgal, large). When a gravity map is completed, we can tell from the disposition and value of the isogals just how much deficiency or excess of mass there is under the area and whether the land surface will rise or fall to attain isostatic equilibrium. Where there are no gravity anomalies, it is probable that the crust is in isostatic equilibrium, and so the situation at depth is analogous to that shown in Figures 23a and 23d.

In what part of the Earth's interior do you think it likely that movement of material can take place in order that isostatic adjustment can occur (*Hint* Think back to Unit 4.)

The asthenosphere, or 'weak-sphere'.

You should now understand the concept of isostasy and how gravity anomalies can be used to detect departures from crustal isostatic equilibrium and be able to demonstrate your understanding of the concepts by interpreting given data concerning actual or hypothetical crustal models.

To test your grasp of this objective, try SAQs 7 and 8.

SAQ 7 Examine Figure 24. Indicate which model will give a negative and which will give a positive gravity anomaly, and which model will show the largest positive and negative anomalies, given that block (b) is in isostatic equilibrium and all blocks have the same density.

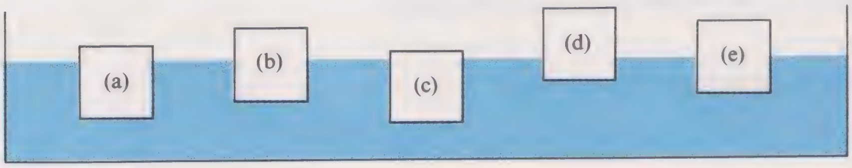


FIGURE 24 Woodblocks in water. Block (b) is floating freely, and so is in isostatic equilibrium. For use with SAQ 7.

SAQ 8 Figure 25 shows the amount of uplift of Scandinavia since the melting of the ice-cap that covered the region some 10 000 years ago. Would you expect the northern Baltic Sea region to be characterized by a negative or positive gravity anomaly?

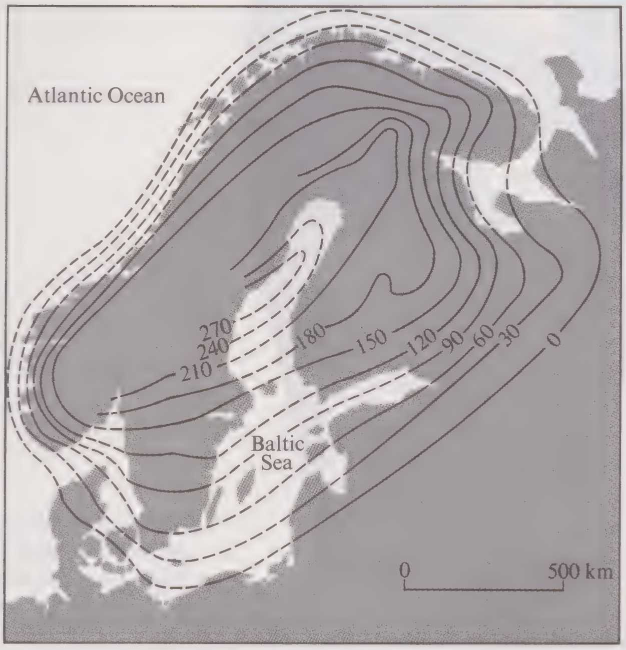


FIGURE 25 Map showing the amount of uplift of Scandinavia since the melting, about 10 000 years ago, of the ice-cap that covered the region. The area is still being uplifted today. Contours are in metres of uplift.

Now to return to the large negative gravity anomalies associated with ocean trenches.

What do the negative gravity anomalies indicate about trenches? Are they topographic features that are in isostatic equilibrium or is something 'holding down' this part of the crust to produce a depression?

Clearly, trenches are not in isostatic equilibrium for, like the Scandinavian region discussed in the answer to SAQ 8, there must be a mass deficiency under them. But unlike the Scandinavian region, where the rate of isostatic adjustment can be observed, trenches appear to be held down by some force. This possibility that the crust was being held down, out of equilibrium, led Vening Meinesz to suggest that they might be associated with the downward moving parts of convection currents (compare with Holmes' and Du Toit's ideas shown in Figure 18).

In the 1950s Hugo Benioff, of the California Institute of Technology, was able to take advantage of improved seismic techniques to plot with considerable accuracy the location and depth of earthquake foci associated with ocean trenches. He found that there are sloping zones of earthquake activity associated with trenches that are inclined towards the continents. These inclined earthquake zones are now known as *Benioff zones*. If you refer back to Figures 10 and 11, you can see some of the larger Benioff zones around the Pacific, for they are the only regions where deep-focus earthquakes occur.

Benioff zones

Figure 26 is a block diagram showing the topography and earthquake distribution at depth in the region of the Japan islands; the negative gravity anomaly over

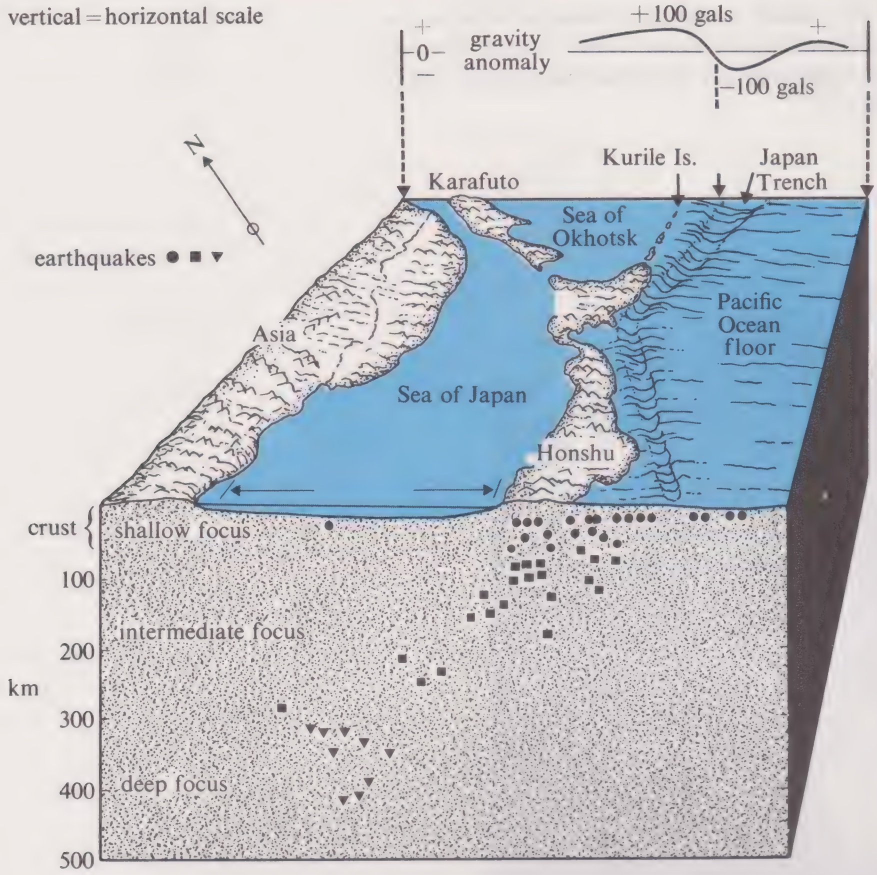


FIGURE 26 Block diagram showing trench off the Japan islands, and associated gravity anomalies and earthquake activity.

the trench is also shown, together with an associated positive anomaly over the islands themselves.

> **ITQ 2** What other kind of geological activity is associated with Benioff zones?

Can you think of any relatively simple measurements that might help confirm the idea that trenches are over the sites of descending convection currents and oceanic ridges over rising currents?

Measurements of the amount of *heat* flowing from the crust in trenches and elsewhere, would, if the convection hypothesis were correct, be lower over trenches than in other regions. Such measurements are the topic of the next Section.

4.5 Oceanic heat flow

Instruments capable of measuring 'heat flow' in oceanic crust were only developed after the Second World War, although such measurements on land had been made since the end of the nineteenth century. Basically, the technique of heat-flow measurement is quite simple: temperature measurements at two depths are needed, plus a measure of the thermal conductivity* of the material in between.

On land, heat-flow measurements can be made in mineshafts or boreholes, so that it is quite easy to get a large spacing between the temperature measurement points. Fortunately, measurements beneath the deep-ocean floor are not complicated by seasonal changes in temperature (because deep-ocean water generally stays at the same temperature throughout the year, crustal temperatures, unlike those beneath land surfaces, are not subject to seasonal variation), so it is not necessary to have a large spacing between the measurement points.

* We do not need to discuss a precise quantitative definition of 'thermal conductivity' here; at a qualitative level the concept is familiar in everyday life. Fill a metal container with boiling water, and almost immediately its outer surface is too hot to touch. But in a plastic or china container the outflow of heat from the hot inner surface is much slower, so for a while at least you could pick the container up. The difference between the speed at which the outer surface of the two containers heats up is largely a reflection of their different conductivities, metal having a higher conductivity than plastic or china.

Before oceanic heat-flow measurements were made, it was confidently expected that such values would be *lower* than those obtained on land. The reason behind this expectation was that there was likely to be a higher concentration of radioactive heat production in the continental crust than contained in the oceanic crust that was assumed to underly the oceans. To the surprise of all concerned, the oceanic heat-flow values turned out to be much the same as those for the continents. Later observations of oceanic heat flow showed that whereas ocean basin floors show 'average' heat-flow values, ocean ridges are 'hotter', and trenches 'cooler' (see Figure 27). Bullard, who had contributed to early designs of the apparatus used to gain the first unexpected results, suggested that convection currents in the mantle, rising under ocean ridges and plunging beneath the continents at the sites of ocean trenches, would account for the newly gained data. Thus, oceanic heat flow is due to heat being transferred from the mantle to near the surface of the crust via convection currents, whereas continental heat flow is largely due to the heat released over a long period of time by radioactive material present in continental crustal material.

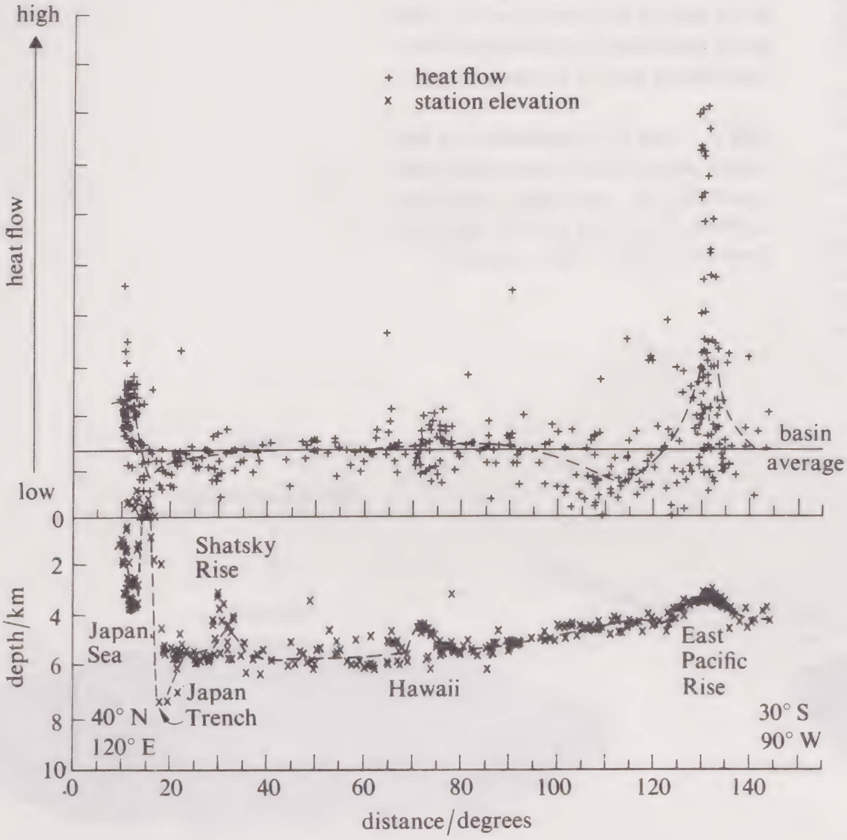


FIGURE 27 Profile of heat flow and topography across the Pacific. Heat-flow units are not defined in this Course; the main point to note is that heat-flow values are well above average over the East Pacific Rise, and below average in the Japan trench.

4.6 An essay in geopoetry

In 1960, Hess circulated a draft of a paper that was not formally published until 1962, but even in its 'pre-print' form (the term used by scientists when circulating drafts of papers to colleagues) it had a profound influence on other workers. Hess called his paper 'an essay in geopoetry', and introduced it by concisely summarizing the contemporary state of knowledge of the oceans by stating 'The birth of the oceans is a matter of conjecture, the subsequent history is obscure, and the present structure is just beginning to be understood'. The paper contained no new data; it was speculation based on a synthesis of existing knowledge.

Hess was struck by the uniformity of the thickness of the layers within oceanic crust as deduced from seismic studies (see Figure 28) and wondered what kind of process was responsible. He was sure that outpourings of basaltic lava (which were known to floor the oceans beneath a thin layer (layer 1) of sediments) would not produce uniform layering, as they would thicken towards the vent or fissure from which the lava came. The details of the process suggested by Hess to account for the uniform layering need not concern us here, but the conclusions that followed from it are extremely important, and had a profound effect on the interpretations made by other researchers in the 1960s.

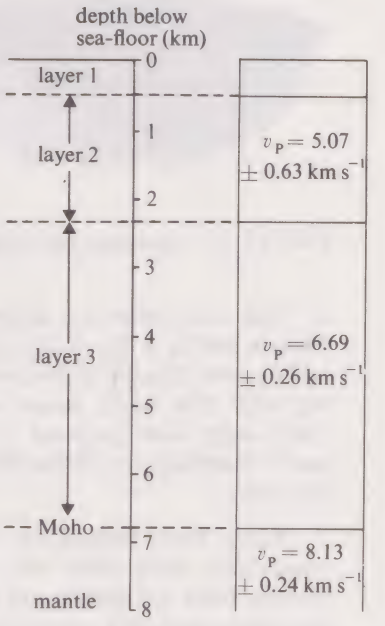


FIGURE 28 Seismic layers of oceanic crust; the thickness of the layers is remarkably uniform over all the oceans. The column shows the thickness of each layer, and its velocity of P-wave transmission. The nature of the rocks forming these layers will be discussed in Section 5.

The most important speculations made by Hess are outlined as follows, and opposite some of them are ITQs which will require you to consider both how they were arrived at, and their significance in interpreting the origin of some of the features you have already studied. *It is important to note that when Hess made these speculations, knowledge of the age distribution of rocks flooring the ocean was extremely scanty. The information given in Figure 8 did not exist at that time, therefore you should not use it when answering these questions.*

Hess's speculations

1 'The mantle is convecting at a rate of 1 cm yr^{-1}' and the 'convecting cells have rising limbs under the mid-ocean ridges'.

Hess reached a figure of 1 cm yr^{-1} by assuming that the South Atlantic had formed when South America and Africa broke apart, the timing of which was not known in 1960. Hess assumed that break-up began roughly 250 Ma ago; the South Atlantic is approximately 5 000 km wide in the equatorial region. So the Atlantic opened 5×10^8 cm (5 000 km) in 25×10^7 years (250 Ma) which is 2 cm yr^{-1}. But the movement on each limb of the convection cell is half this figure: 1 cm yr^{-1} (see Figure 29).

ITQ 3 Figure 20c provides a more precise date for the time the South Atlantic began to open, for it is probable that the occurrence of salt marks the influx of seawater into a narrow gulf between the two continents. What rate of movement on *one* limb of the postulated convection cell does this revised date of opening give?

ITQ 4 Hess cited evidence that supported the idea that ocean ridges are underlain by upwelling convection currents. You have already met *three* lines of evidence: what are they?

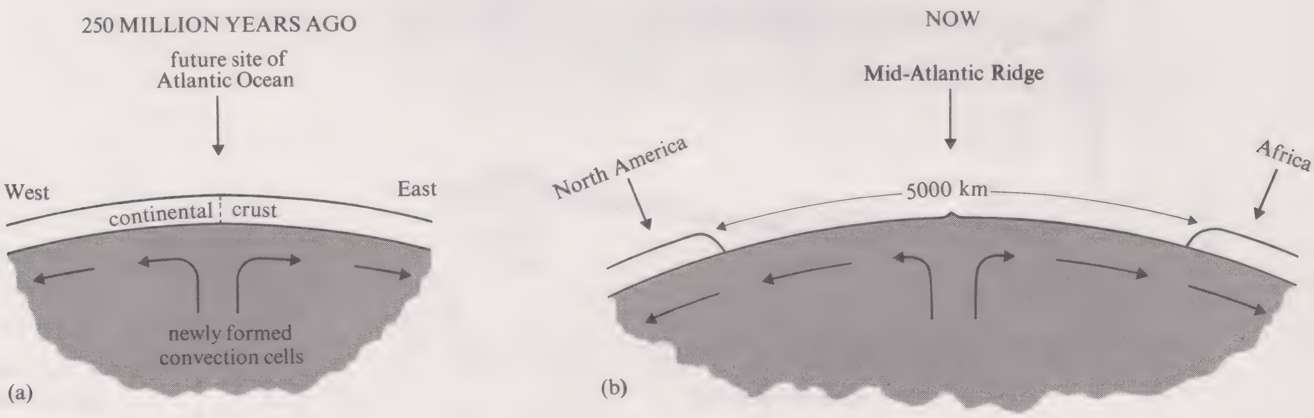


FIGURE 29 Convection cells and Atlantic opening. For use with ITQ 4.

2 'Mid-ocean ridges are ephemeral features having a life of 200 to 300 million years (the life of the convecting cell).' 'The whole ocean is virtually swept clean (replaced by new mantle material) every 300 to 400 million years.'

ITQ 5 What observation would most aid the verification of these speculations? This is not a catch question—the answer is quite simple!

3 'Rising limbs coming up under continental areas move the fragmented parts (of continents) away from one another at a uniform rate so a truly median ridge forms as in the Atlantic Ocean.'

4 'The continents are carried passively on the mantle with convection and do not plough through the oceanic crust.'

ITQ 6 How does this description differ from Wegener's concept of drifting continents?

5 The leading edges of continents 'are strongly deformed when they impinge upon the downward moving limbs of convecting mantle'. 'The oceanic crust, buckling down into the descending limb, is heated ... 'The cover of oceanic sediments and the volcanic seamounts also ride down into the jaw crusher of the descending limb, are metamorphosed* and eventually are probably welded onto continents.'

ITQ 7 You have already met evidence that favour these ideas of the leading edges of continents being deformed and oceanic crust 'buckling down'. We have not described such features in terms of Hess's speculation, but you should be able to suggest *two* phenomena that fit in with his ideas.

Hess concluded his paper with the following statement: '... the writer has attempted to invent an evolution for ocean basins. It is hardly likely that all the numerous assumptions made are correct. Nevertheless it appears to be a useful framework for testing various and sundry groups of hypotheses relating to the oceans. It is hoped that the framework with necessary patching and repair may eventually form the basis for a new and sounder structure'.

Hess himself did not coin the term 'sea-floor spreading' even though he described it! In 1961, Robert S. Dietz of the US Navy Electronics Laboratory in California published a paper in *Nature* (a widely read weekly scientific journal published in Britain) that explored the consequences of Hess's ideas for the evolution of mountain belts and ocean basins, and at a later date gave Hess full credit for the concept to which he (Dietz) had given such an attractive name.

As we shall see, Hess's sea-floor spreading idea was confirmed by a variety of independent lines of investigation during the early 1960s.

4.7 A sea-floor tape recorder

During the Second World War, advances in techniques of submarine detection had led to the development of very sensitive airborne magnetometers, and after the war, devices were designed for towing behind ships. These instruments are very sensitive; they are able to detect extremely small fluctuations in the Earth's total magnetic field, which are caused by the tiny amounts of magnetic material present in crustal rocks. Thus a reading obtained by a magnetometer at any point of the Earth's surface is produced by:

1 the dipole field;

2 the non-dipole field;

3 small variations in the total field caused by magnetic materials present in crustal rocks.

The dipole and non-dipole field (items 1 and 2) probably have an internal 'hot' origin, due to convection currents in the Earth's outer core, whereas the small local variations in the Earth's magnetic field result from the magnetic properties of the cold crust.

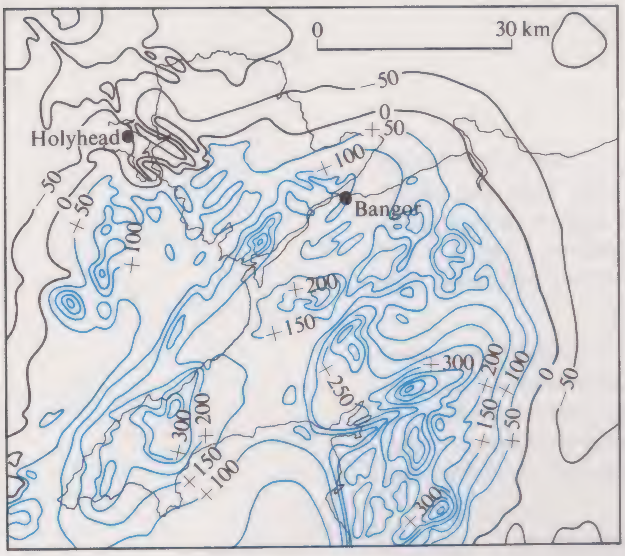
It is item 3 that concerns us here; this produces variations of between 0.1 and 1.0 per cent of the Earth's total magnetic field, and so it was not discussed when we dealt with magnetism on a global scale in Unit 5. However, it is the most useful component of the Earth's magnetic field, for it can be used to aid the location of certain rock types buried several kilometres down, or concealed by the oceans. Maps showing the local variations in the Earth's magnetic field after the dipole field and non-dipole field (items 1 and 2) have been subtracted show *magnetic anomalies*, the patterns of which offer clues concerning the nature of the underlying rocks. Thus the pattern of magnetic anomalies may reflect both the amount of magnetic materials present in the underlying rocks and the orientation of the geomagnetic field at the time when any igneous rocks cooled below their Curie

* Metamorphism is the process by which existing rocks are changed at depth within the Earth by the effects of heat and pressure. A simple analogy, only involving heat, is the firing of clay to produce bricks and pottery. The process is explained in more detail in Unit 27.

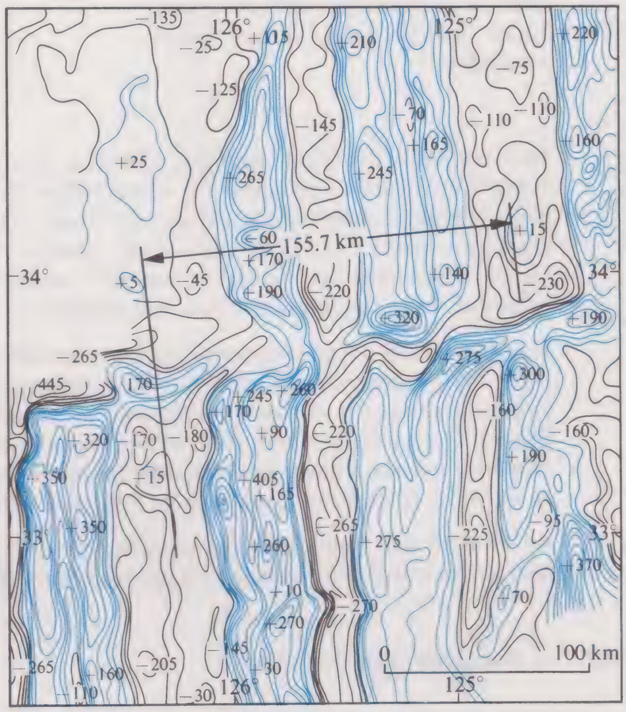
temperatures. The anomalies that are plotted on the basis of such measurements are extremely small, only plus or minus 0.1 per cent to 1.0 per cent of the Earth's total field. (Examples of magnetic anomaly maps are shown in Figure 30.)

Early surveys in the 1950s showed that the axial rift of the Mid-Atlantic Ridge possessed a marked positive magnetic anomaly, but later, more detailed, work showed that ocean basins possessed a remarkably linear anomaly pattern, quite unlike anything seen on continents (compare Figure 30a with Figure 30b).

linear magnetic anomalies



(a)



(b)

FIGURE 30 Magnetic anomaly patterns showing variations in the Earth's magnetic field produced by variations in the magnetic properties of crustal rocks. Contour intervals are in 100 gammas (one gamma = 1×10^{-9} T); positive values are shown in blue. The contours are plotted using observations from which the Earth's total field (about $50\,000 \times 10^{-9}$ T) has been subtracted.

(a) A continental area (North Wales) showing characteristic magnetic anomaly pattern of rounded contour distributions.

(b) An oceanic area west of California showing characteristic linear magnetic anomaly pattern (often described as magnetic stripe anomalies) which has been displaced sideways by 155 km by a large fault (see Figure 32).

In 1955, the U.S. Coast and Geodetic Survey began very detailed submarine mapping off the west coast of North America in connection with the development of navigation systems for American nuclear submarines. Despite the top secret nature of the results of this work, the Survey offered to tow a magnetometer from the Scripps Institute of Oceanography behind their ship which traversed the Pacific off western North America in a series of east–west tracks spaced at 8 km intervals. The results of the magnetic survey (published in 1961) are shown in Figure 31a. They showed a pattern of magnetic anomaly stripes traversing the area and cut and displaced sideways (Figure 31b) by a number of what appeared to be tear faults (see Figure 32c, p. 46).

The initial survey had not been extensive enough to reveal the amount of displacement along the fractures, but later surveys showed them to have displacements of several hundred kilometres, with the Mendocino Fracture Zone (see the *World Ocean Floor* chart) to have a displacement of 1 100 kilometres. Such large movements questioned the assumption made by continental geologists that crustal movements are predominantly vertical. Both the stripes and the fractures were totally new features, unlike anything that had been surveyed on the continents. At first oceanographers were at a loss to explain the origin of the magnetic stripes; suggestions ranged from systems of electric currents flowing in the crust, to magnetization induced by stresses in the crust associated with the building of the mountain ranges along the coast. Arthur Raff, who had initiated the Scripps Survey, did, however, comment that the stripes seemed to run parallel to ocean ridges, and so thought the two features might be related—at the time, little did he know how right he was.

(a)

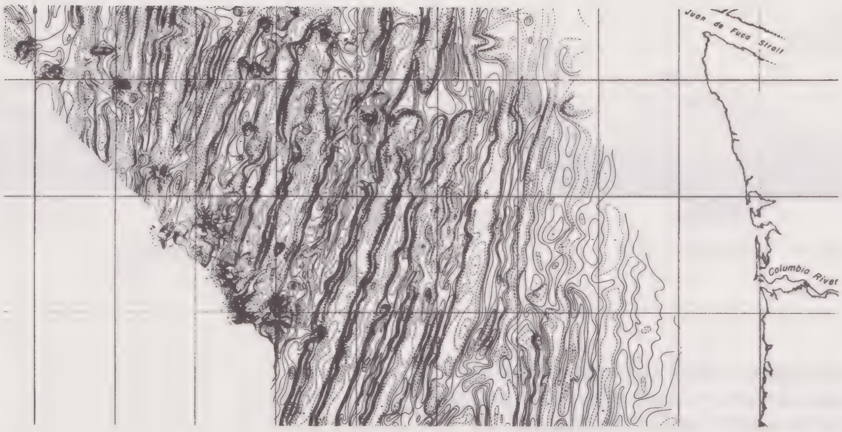
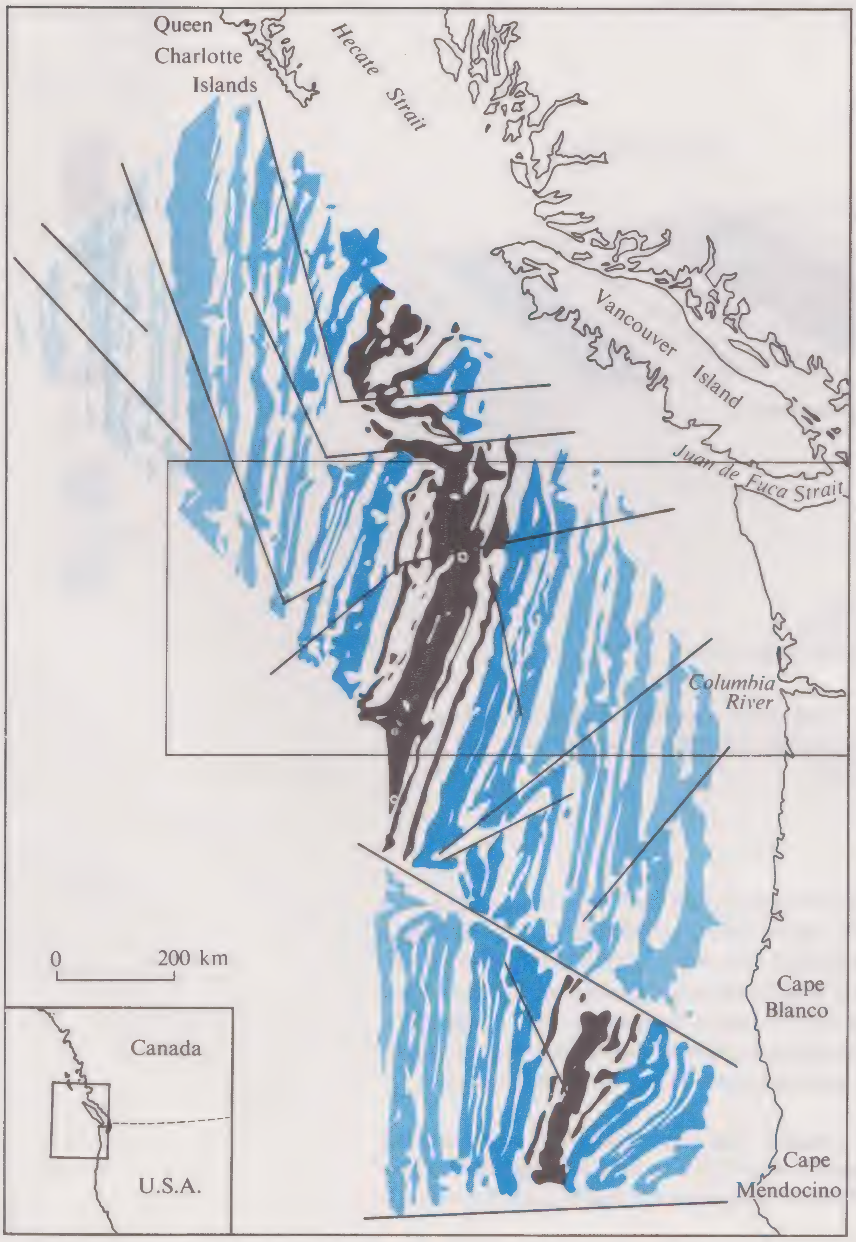


FIGURE 31 Results of magnetic survey carried out off western North America in 1955 and 1956, published in 1961.

(a) A portion of the survey showing contour pattern of magnetic anomalies. The location of this map is shown by the box in the centre of Figure 31b.

(b)



(b) Data covering a larger area than that shown in (a) simplified to show areas where magnetic intensity is higher than average (black or blue—the significance of the use of black and different tones of blue will become apparent in the next few pages), and lower (white). Black straight lines are interpreted as positions of major tear faults (see Figure 32).

Note that when these 'magnetic maps' were first published, the locations of the Juan de Fuca Ridge and the Gorda Ridge (both ocean ridges) were not generally known, as the results of bathymetric surveys were still classified information!

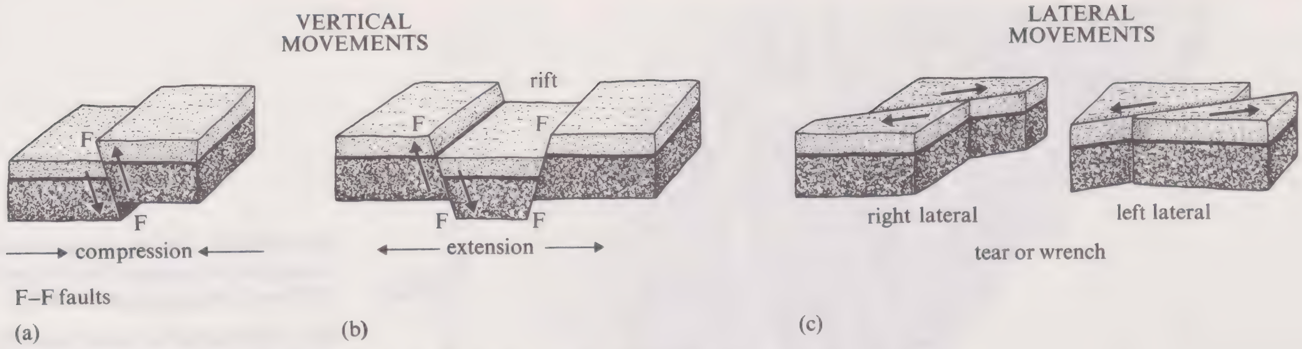


FIGURE 32 Block models illustrating geological faults. Until magnetic surveys of ocean basins revealed many large faults with large sideways or lateral movements, geologists had considered that most faulting involved predominantly vertical movements.

ITQ 8 How would *you* interpret the striped magnetic anomalies discovered on the floor of the Pacific to the west of the United States and Canada, given that (a) you are already aware of some of Hess's speculations (especially the first one summarized on page 42), and (b) you know that the polarity of the Earth's magnetic field suffers periodic reversals (see Unit 5, Figure 23)? Figure 33 should help your speculations! It is essential that you do not skip reading the answer to this question.

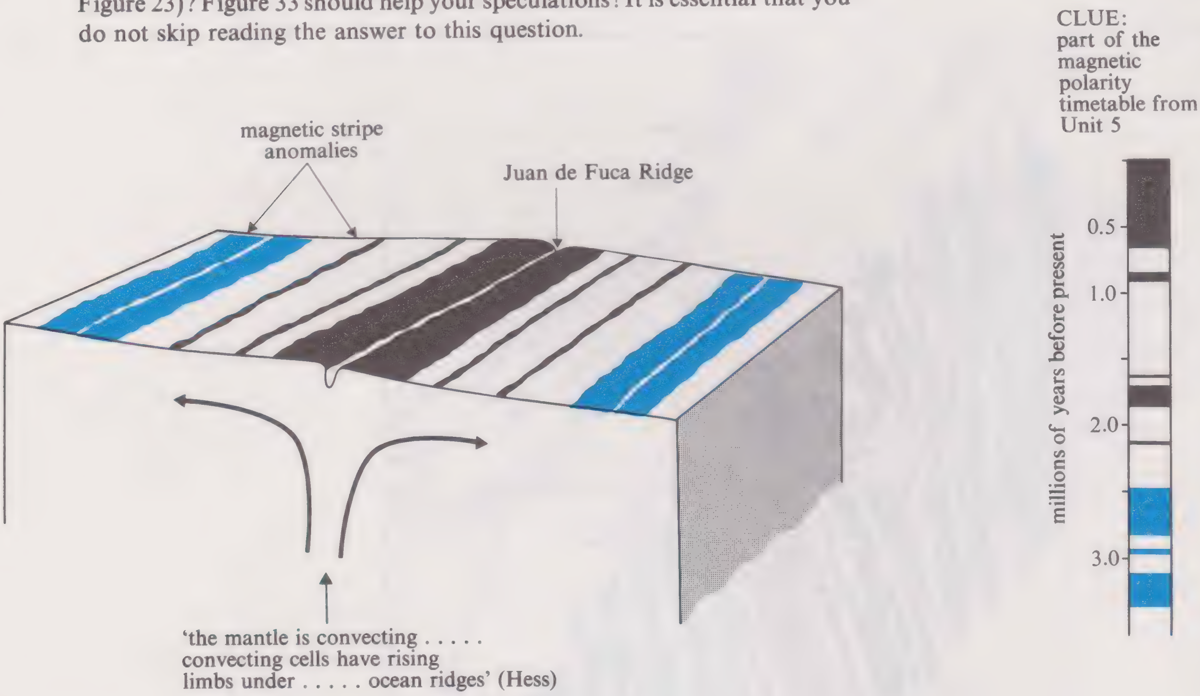


FIGURE 33 A sketch block diagram of part of the sea-floor shown in the box in the centre of Figure 31b, incorporating Hess's speculation that mantle is convecting, with rising cells under ocean ridges. For use with ITQ 8.

In 1962, Drummond Matthews of the University of Cambridge conducted a very detailed magnetic survey of a small region (just over 600 km^2) of the Carlsberg Ridge in the Indian Ocean (see the *World Ocean Floor* chart). Later that year and early in 1963, Fred Vine, then newly graduated from Cambridge, worked on the data obtained from the Carlsberg Ridge, and in September 1963 published a paper jointly with his supervisor (Matthews) with the rather insignificant sounding title 'Magnetic anomalies over oceanic ridges'. They wrote as follows:

> Work on this survey led us to suggest that some 50 per cent of the oceanic crust might be reversely magnetized and this in turn has suggested a new model to account for the pattern of magnetic anomalies over the ridges.

linear magnetic anomalies and reversals

The theory is consistent with, in fact virtually a corollary of, current ideas on ocean floor spreading and periodic reversals in the Earth's magnetic field*. If the main crustal layer of the oceanic crust is formed over a convective up-current in the mantle at the centre of an oceanic ridge, it will be magnetized in the current direction of the Earth's field. Assuming impermanence of the ocean floor, the whole of the oceanic crust is comparatively young, probably not older than 150 million years, and the thermo-remanent component** of its magnetization is therefore either essentially normal, or reversed with respect to the present field of the Earth. Thus, if spreading of the ocean floor occurs, blocks of alternately normal and reversely magnetized material would drift away from the centre of the ridge and parallel to the crest of it.

This configuration of magnetic material could explain the lineation or 'grain' of magnetic anomalies observed over the Eastern Pacific to the west of North America.

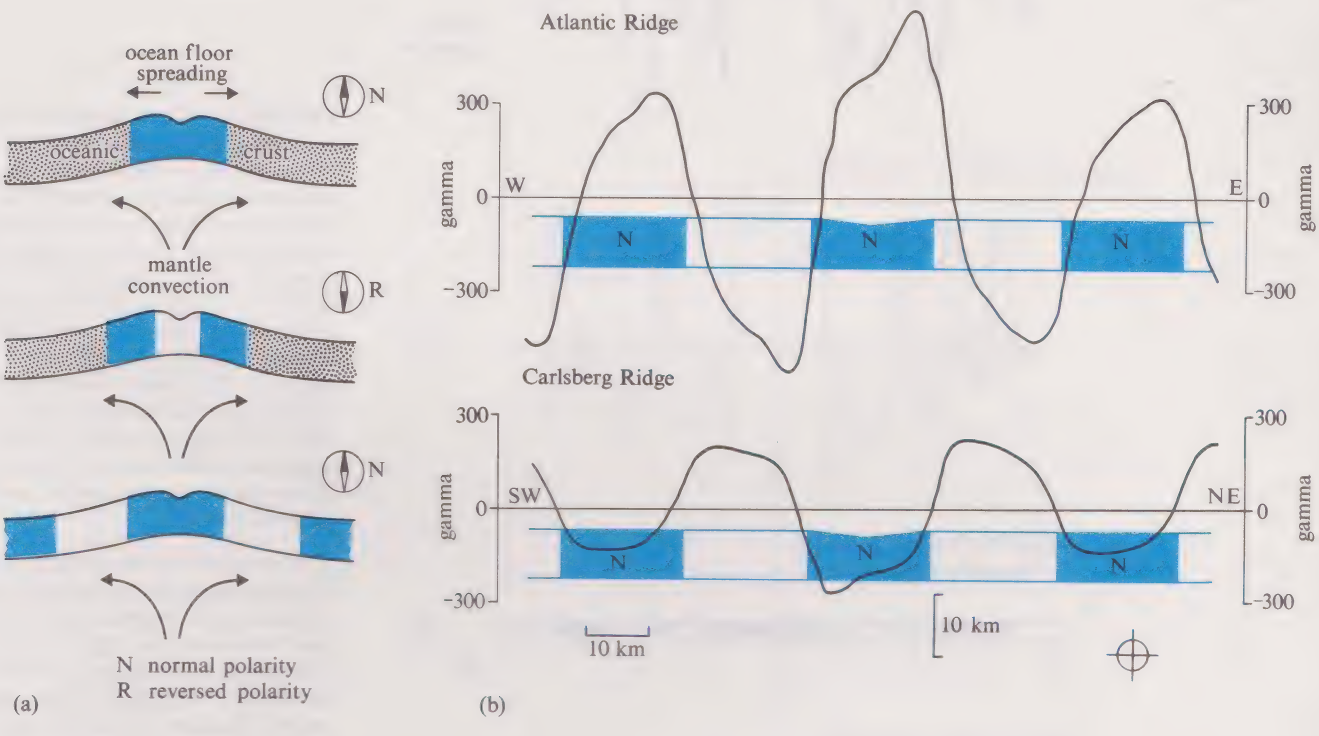


FIGURE 34

(a) The Vine–Matthews hypothesis linked Hess's ideas concerning mantle convection with the new discovery that the Earth's magnetic field suffers periodic polarity reversals. Vine and Matthews assumed that alternate periods of normal and reversed polarity are recorded in ocean-floor rocks during the spreading process.

(b) Using the model depicted in (a), Vine and Matthews were able to compute magnetic profiles that would be produced for the Atlantic and Carlsberg Ridges (one gamma = 1×10^{-9} T).

The paradox that a negative gamma value over the Carlsberg Ridge is interpreted as being produced by a strip of normally magnetized ocean crust is due to the inclination of the present geomagnetic field being almost zero, and the orientation of the remanent field is nearly parallel to it. The full explanation need not concern you.

The Vine–Matthews hypothesis is explained in Figure 34. Initially, there was very little reaction to it and it was only when it was developed further, and more evidence cited to favour it, that the bandwagon of sea-floor spreading really began to roll.

* See Unit 5, Figure 23; although in 1963 the reversal time scale was not known in such detail.

** This is the remanent magnetic field frozen into the ocean crust when it cools past the Curie point of the magnetic materials within it (see Unit 5).

In 1965, Vine and the Canadian, Tuzo Wilson, published a paper interpreting a small part of the magnetic survey shown in Figure 31a. They postulated that the anomaly stripe trending NNE towards Vancouver Island (see Figure 31b) was a small section of an ocean ridge (the Juan de Fuca Ridge), and applied the Vine–Matthews hypothesis to the existing data. By now, a timetable of reversals in the polarity of the Earth's magnetic field had been worked out (although not in as

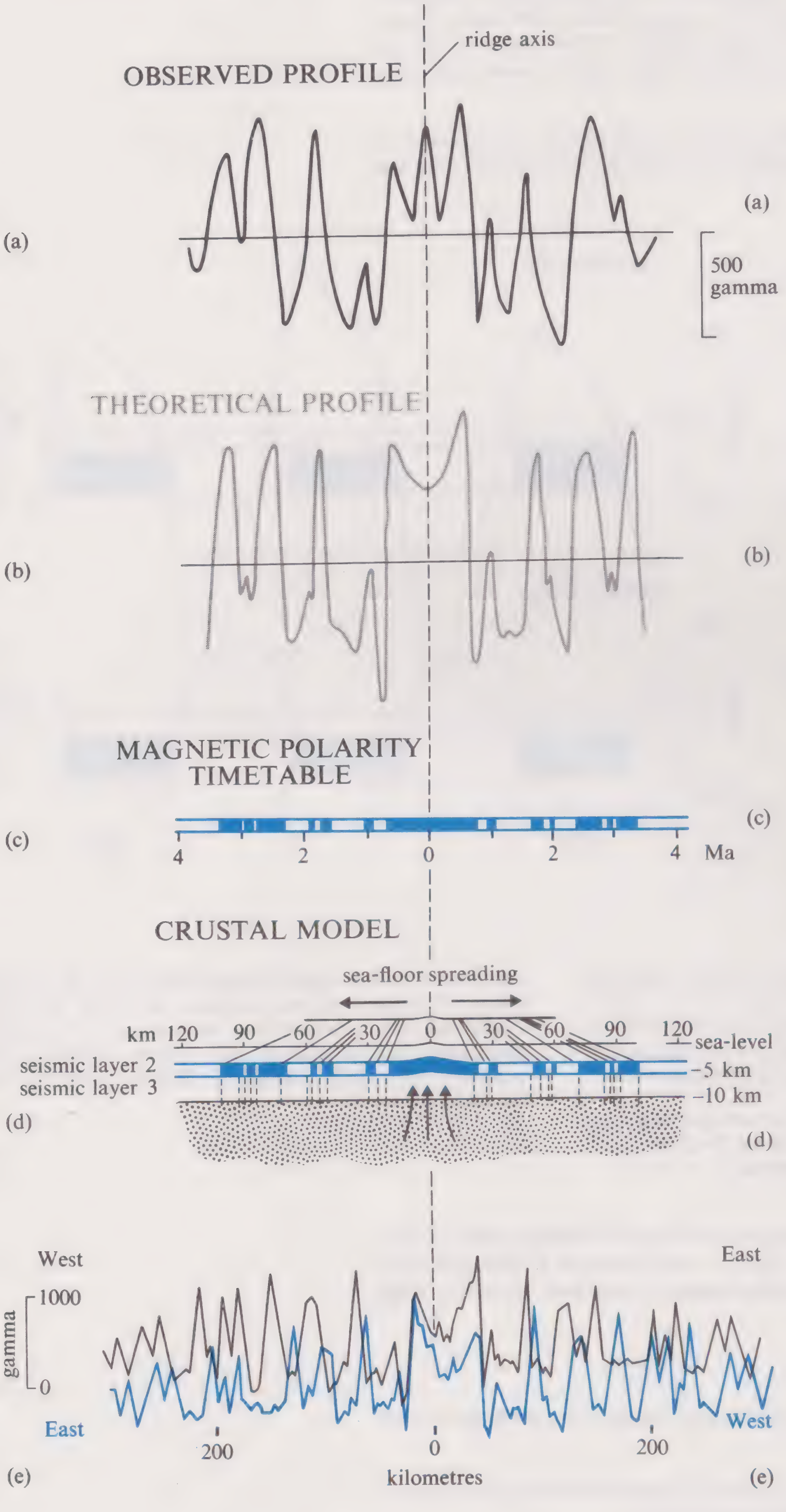


FIGURE 35 Vine's model for the Juan de Fuca Ridge (for location see Figure 31b), first published in 1968. By this time, the timetable of polarity reversals of the Earth's magnetic field back to about 4 million years ago was known. In this illustration, this 'timetable' (Unit 5, Figure 23) is turned on its side (c) to equate with the magnetization of ocean crust, and used to compute a theoretical profile for the Juan de Fuca Ridge (b). This profile is calculated from knowledge of the Earth's present geomagnetic effect in the region, plus the predicted additional effects of strips of ocean floor alternately showing normal and reversed magnetic polarity.

This theoretical profile compares well with the observed profile (a), providing evidence in favour of the hypothesis that new ocean crust forms over the ridge, and then spreads sideways as a consequence of mantle convection. This being so, the magnetic polarity timetable (c) can be related to the magnetic stripe anomalies observed on either side of the Juan de Fuca Ridge (d), and so equated to successive magnetic polarity events. (*Note* The Gilsa event at about 1.6 Ma is too small to show on this diagram.) As the ages of the epochs are known from palaeomagnetic studies of accessible lava sequences on continents, these ages can be applied to the sea-floor magnetic stripe anomalies, and a rate of sea-floor spreading calculated. Thus variations in the Earth's magnetic field through time are recorded in sea-floor rocks, much like signals on the magnetic tape of a tape recorder. They are even in stereo, with identical signals recorded on each side of the ridge! In 1966, data obtained during a survey of the East Pacific Ridge were published (e), and showed that the magnetic profile on one side of the ridge mirrored that on the other—just what was expected from the Vine–Matthews 1963 hypothesis. (The blue profile is a mirror image of the black one.)

much detail as that shown in Unit 5, Figure 23) and this could be incorporated into the model. The only piece of information missing was the rate of spreading, but their model enabled this to be calculated.

> Figure 35 shows Vine's later model for the Juan de Fuca Ridge; from it you should be able to calculate the sea-floor spreading rate that best fits the observations.
>
> Figure 35d shows the ages of the magnetic anomaly stripes on either side of the Juan de Fuca Ridge. For example, the ocean floor 90 km from the ridge crest gives a magnetic anomaly profile that matches reasonably well to the 3 million year section of the theoretical profile. Therefore, in one million years, 30 km width of new ocean floor was formed on one side of the ridge, giving a spreading rate of $3\,\text{cm}\,\text{yr}^{-1}$.

Vine and Matthews may have been first to get into print the sea-floor tape recorder idea, but they were not the only scientists to come up with this concept. In February 1963, L. W. Morley of the Geological Survey of Canada submitted an account of the implications of combining Hess's ideas on the origin of the oceans by mantle convection with the new timetable of magnetic polarity reversals. Part of the draft of a paper he wrote read as follows:

> If one accepts in principle the concept of mantle convection currents rising under ocean ridges, travelling horizontally under the ocean floor and sinking at ocean troughs, one cannot escape the argument that the upwelling rock under the ocean ridges must become magnetized in the direction of the Earth's field prevailing at the time. If this portion of rock moves upward and then horizontally to make room for new upwelling material, and if, in the meantime, the Earth's field has reversed, and the same process continues, it stands to reason that a linear magnetic anomaly pattern of the type observed would result. This explanation has the advantage over many of the others put forward that it does not require a petrologically*, structurally, thermally, or strain-banded oceanic crust. It requires a convection cell whose axis of rotation is at least as long as the linear magnetic anomalies, and whose horizontal distance of travel stretches from ocean rise to ocean trough. In addition to this, it requires a large number of reversals of the earth's magnetic field from at least the Cretaceous period** to the present (since no rocks older than Cretaceous** have been found in the ocean basins).

Dr Morley submitted his article to *Nature*, and it was turned down. He then sent it to the *Journal of Geophysical Research* (an American journal), which also rejected it. One of the reviewers of the paper commented:

> Such speculation makes interesting talk at cocktail parties, but is not the sort of thing that ought to be published under serious scientific aegis.

So, good luck and bad luck can influence scientific success. The Vine and Matthews paper was published by *Nature* in September 1963; the main difference between their contribution and that of Morley's was that they were also reporting the results of a new survey (of the Carlsberg Ridge), whereas Morley was synthesizing and explaining already published data.

* 'petrologically ... banded oceanic crust' means crust whose rock composition changes laterally, rather than staying as uniform basalt.

** As you will see in Unit 26, geological time is divided into segments which are given different names. The Cretaceous period ended about 70 Ma ago, and began about 135 Ma ago.

4.7.1 Objective of Section 4.7

You should now be able to

(a) Demonstrate your understanding of the hypothesis of sea-floor spreading by summarizing the evidence that supports it, and by carrying out calculations based on sea-floor magnetic anomaly data.

Now try applying the knowledge you have gained in the preceding Sections by answering SAQs 9–12, which relate to Objective (a).

All these questions should be answered using the data given in Figure 36. (Make your calculations using the *observed* profile.)

SAQ 9 What is the mean spreading rate for the South Atlantic?

SAQ 10 What is the age of the South Pacific Ocean Floor 350 km out from the ridge?

SAQ 11 What was the spreading rate of the South Pacific between 0 and 10 Ma ago?

SAQ 12 What was the spreading rate in the South Pacific between 10 and 30 Ma ago?

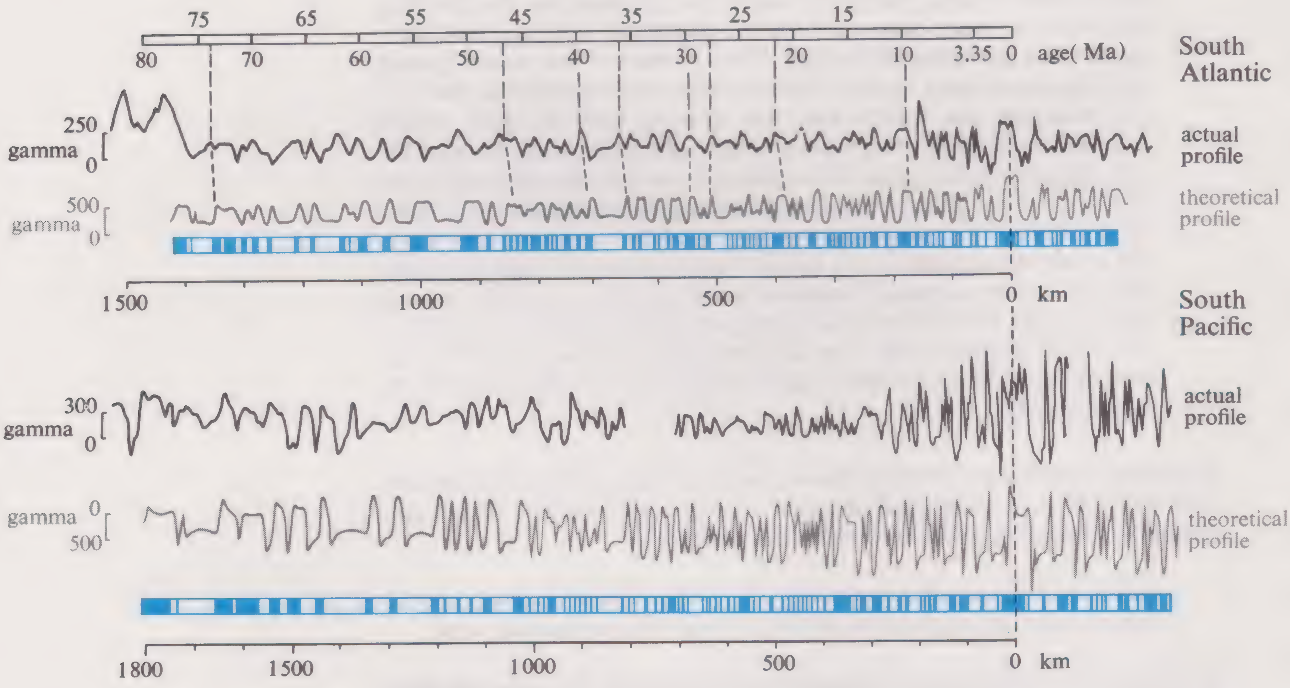


FIGURE 36 Magnetic anomaly profiles across the western flanks of the ocean ridges in the South Atlantic and South Pacific. The spreading rate in the South Atlantic is assumed to be constant so that the age of the ocean floor beyond one hundred or so kilometres from the ridge crest can be determined by extrapolation. Thus 1 400 km from the crest the ocean floor is interpreted to be 77 Ma old. In this way, the magnetic reversal timetable has been extended back in time beyond 4 Ma ago—the original limit that was possible using measurements from continental lava sequences (see Unit 5, Figure 23). For the South Pacific the observed profiles are compared with computed profiles that assume the same sequence of reversals of the Earth's magnetic field *but* variations in spreading rate.

You will have gathered from these exercises that:

1 examination of anomaly profiles provides a means of dating the sea-floor (without taking samples from it and dating them);

2 there are variations in the rates of sea-floor spreading between oceans, and through time.

However, these conclusions are based on the assumption that sea-floor spreading proceeded at a constant rate of 1.8 cm yr^{-1} in the South Atlantic. Critics of the sea-floor spreading hypothesis thought this assumption went too far on the available evidence.

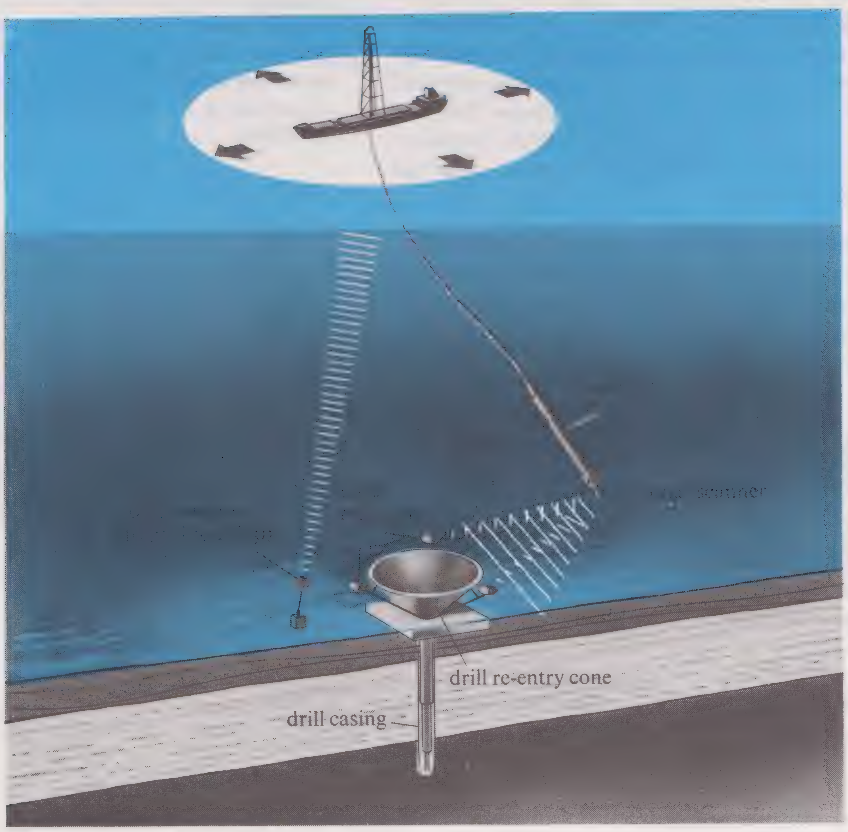
What kind of evidence might prove the assumption to be correct?

If the ocean floor could be sampled (and so dated by direct measurements) at points where the 'anomaly age' was known, the Vine–Matthews hypothesis could be subjected to an independent check.

4.8 Deep-sea drilling

In 1957, Professor Harry Hess and a number of other distinguished American scientists suggested that an attempt should be made to drill a borehole deep enough to penetrate the Mohorovičić discontinuity. The 'Mohole project', as it became known, opted to take the short-cut route to the Moho, through the ocean floor, where it lies a 'mere' 5 km down, in contrast to the 30 km or greater depth under the continents. The story behind the project is a fascinating one; it took place at a time when there was great rivalry between American and Russian scientists, and for a while there was a feeling that there was a 'race to the mantle', but this turned out to be unfounded. In the end, the project foundered because of escalating costs, accusations of political 'bribery' on the part of the main contractor, and doubts about the wisdom of spending so much money on a single attempt to reach the mantle. In August 1966, the project was terminated, but the money

(a)



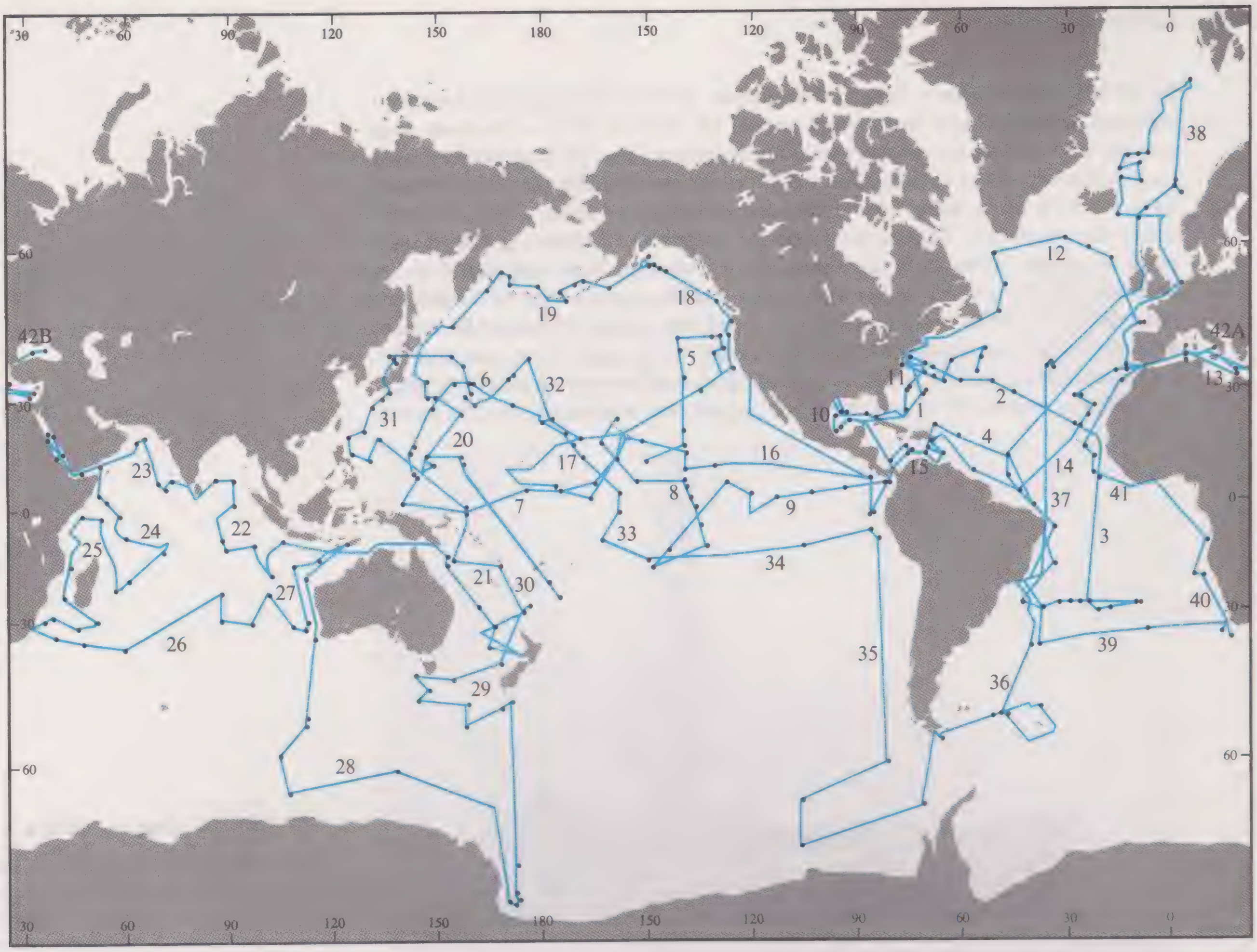
(b)

FIGURE 37 Deep-sea drilling.

(a) The *Glomar Challenger*. Thrusters in the bow and stern of the ship are controlled by computer to maintain it within 30 metres of a point directly above an electronic beacon previously dropped to the bottom. Drilling can thus proceed without danger of breaking the drill string (many lengths of drill pipe attached to the drill bit).

(b) The drilling system. The re-entry cone is attached to the drill string as it is first lowered to the bottom. The cone remains on the bottom when the drill string is withdrawn for the drill bit to be replaced. For re-entry the drill string is lowered, with the attached sonar scanner providing information about the position of the drill bit assembly so that the water jet can be used to steer the bit into the cone. Before 1970, the *Glomar Challenger* operated without the re-entry system, and so the depth of holes drilled was limited by the life of a single drill bit.

FIGURE 37 is continued overleaf.



(c)

FIGURE 37 continued.

(c) Routes covered by the *Glomar Challenger* during the Deep-Sea Drilling Project, August 1968–September 1975. Numbers refer to 'legs', which are cruises of about two months' duration, during which an average of ten sites (each shown as dots) are drilled.

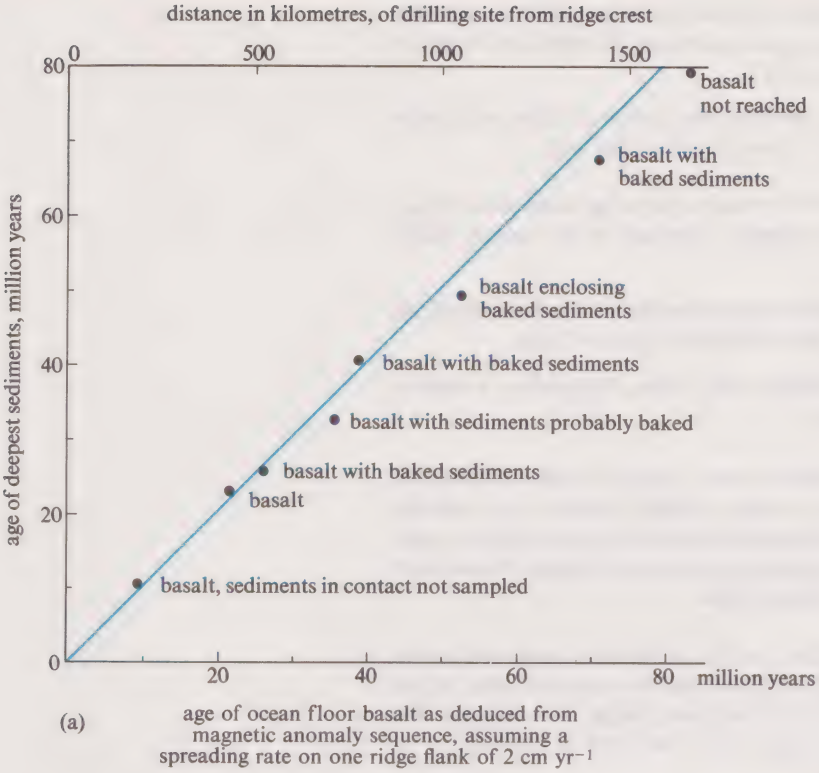
spent on it already ($25 million) was not all wasted, for a new technology for drilling in very deep water had been developed. This technology provided the basis for the Deep-Sea Drilling Project (DSDP) which was organized under the auspices of JOIDES (Joint Oceanographic Institutions for Deep-Earth Sampling), a consortium of five American Oceanographic Institutions. A specially designed ship, the *Glomar Challenger*, was launched in 1968, and has operated continuously since July of that year (see Figure 37). The original project has now been extended to include participation by other nations (France, West Germany, Japan, the United Kingdom and the USSR) contributing to its costs under the International Phase of Ocean Drilling (IPOD).

One of the first tasks of *Glomar Challenger* was to test the sea-floor spreading hypothesis. In early 1969, on the ship's third cruise, a number of holes were drilled at sites on either side of the mid-ocean ridge in the South Atlantic. Basalt was retrieved from most of these holes, and it was dated* by using fossils to determine the age of the overlying sediments.

> On the basis of the previous discussion concerning rates of sea-floor spreading, and the answer to SAQ 9, would you expect a graph of sample age plotted against distance from ocean ridge to show the points falling along a curve, along a straight line, or to show a random pattern?
>
> If the sea-floor spreading rate in the South Atlantic had remained constant throughout its opening, the points on such a graph should fall along a straight line, *providing* true ocean floor had been sampled (see Figure 38 for further discussion).

The results shown in Figure 38 confirmed the hypothesis of sea-floor spreading, *and* the constant rate of spreading postulated for the South Atlantic.

* Methods of dating rocks are discussed in Unit 26.



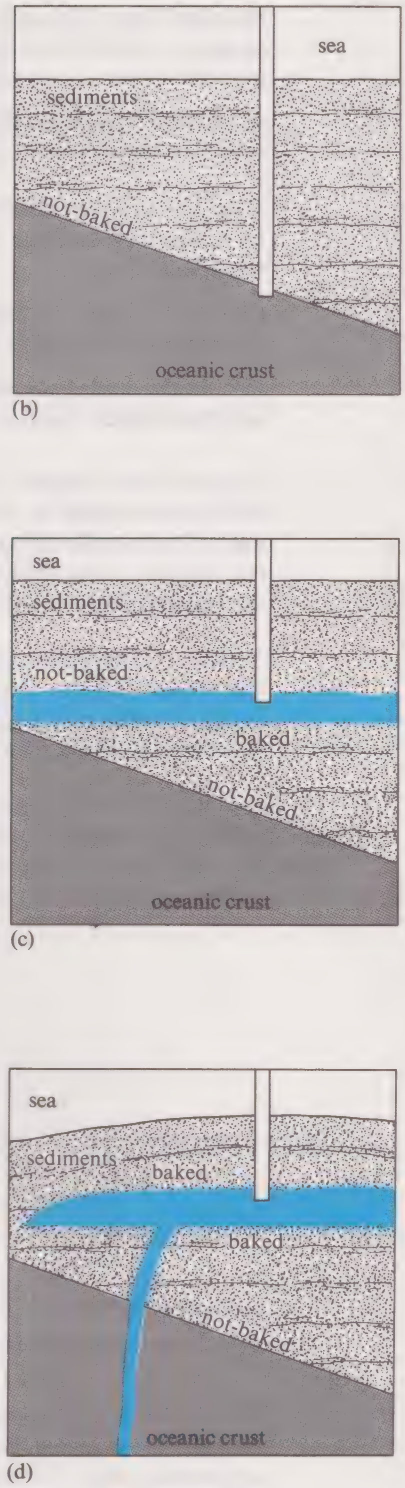


FIGURE 38 Results obtained by the Deep-Sea Drilling Project in the South Atlantic.

(a) The graph shows the age of deepest sediments (determined by studying their contained fossils, see Unit 26) plotted against the distance from the crest of the mid-ocean ridge. All the points fall close to a line representing a spreading rate of $2\,\mathrm{cm\,yr^{-1}}$*, from which the age of the ocean floor is deduced from the magnetic anomaly evidence. However, there are problems in interpreting the information gained from the boreholes. In particular, can the recovery of basalt be assumed to mean that true ocean floor has been reached?

Diagrams (b)–(d) show the possibilities. In all cases the ridge is situated to the left of the diagrams, and so the oceanic crust becomes *older* to the right. Similarly, the age of sediments in contact with basaltic oceanic crust becomes older to the right; these sediments, having been deposited on top of the crust, will not be baked. The ideal case shown in (b) occurs when the sediments penetrated by the deep-sea drill have a similar age to the ocean crust beneath. But lava flows may be poured out over the sediments deposited on top of the crust (c) and in this case there would be no way of distinguishing this situation from (b), unless drilling continued through the lava to the sediments beneath it.

In (d), a body of molten basalt has been intruded into sediments overlying the crust, and has baked the sediments both above and below it (a lava flow (c) only bakes the sediments beneath it). Such baking would not occur at the sediment basalt contact in (b) or (c), yet it was commonly found (as shown on the graph) in the Atlantic sites. Despite this cautionary note, the results of deep-sea drilling are generally considered to offer strong support to the sea-floor spreading hypothesis, for if the situation shown in (d) were a serious problem, the ages of the sample points on the graph should be scattered well away from the $2\,\mathrm{cm\,yr^{-1}}$ line.

4.9 Transform faults

In Section 4.6 we showed how oceanic magnetic anomalies revealed that geological faults with large lateral displacements are common features of oceanic crust, in contrast to faults cutting continental crust which mostly show vertical movement.

* This value differs from that given in the answer to SAQ 7 because the rate of sea-floor spreading in the South Atlantic increases from north to south; the reason for this will become apparent in Section 4.10. The dates plotted in Figure 38a were obtained from samples obtained slightly further south than the magnetic anomaly traverse shown.

Examine Figure 32 (p. 46) once more. Would you expect earth movements along tear faults to produce earthquake epicentres all along the length of the fault, or just along one sector of it?

As one crustal slab is sliding past another, over a period of time earthquake epicentres should occur along the whole length of the fault.

Now locate on the *World Ocean Floor* chart some large faults in the Atlantic comparable to those we have already examined in the eastern Pacific (see Figure 31):

(a) In the North Atlantic, to the south and north of Newfoundland, the Oceanographer Fracture Zone, and the Gibbs Fracture Zone;

(b) In the central (equatorial Atlantic) the Vema, Romanche, Ascension and Rio Grande Fracture Zones.

Once you have located these fracture zones, some of which displace the Mid-Atlantic Ridge by as much as 500 km, decide whether they show the kind of earthquake epicentre distribution you would expect along a major tear fault (i.e. along their entire lengths) by examining Figures 10 and 11 on the fold-out pages at the end of these Units.

You were probably surprised to find that the earthquake epicentres are *not* distributed along the entire lengths of these fracture zones or faults, but are confined to the axial region of the Mid-Atlantic Ridge. This suggests that movement is taking place only along a very small part of the fault.

Figures 10 and 11 are not drawn on a large enough scale for the distribution of earthquakes along fracture zones to be described accurately. More detailed maps show that earthquake activity is confined to the region of the fault between the offset portions of ocean ridge, as shown in Figure 39.

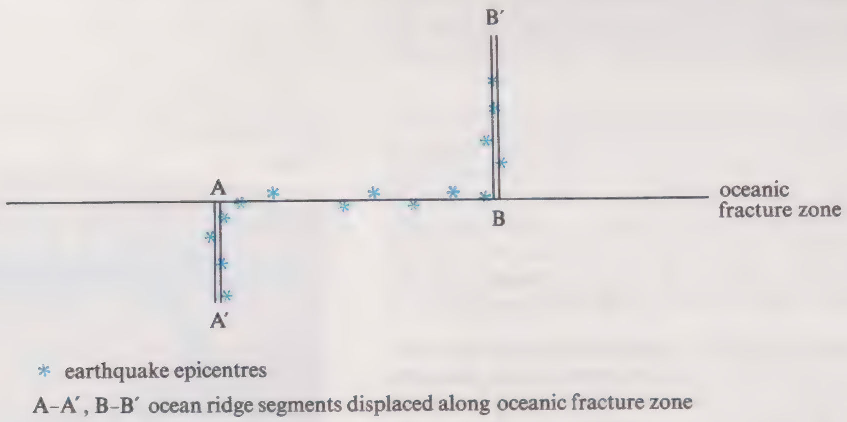


FIGURE 39 A sketch map to show the distribution pattern of earthquake epicentres along ocean ridges cut by fracture zones. For use with ITQ 9.

ITQ 9 What mechanism could account for earthquake epicentres being confined to the region along a fracture zone between the offset portions of an oceanic ridge? To answer this question, draw a series of arrows on Figure 39 to represent the direction of sea-floor spreading. Draw one series of arrows from B to A, and beyond on the south side of the fracture zone, and another series on the north side from A to B′ and beyond. Now you should see the answer! Turn to page 77 for our illustration.

In 1965, Tuzo Wilson offered the explanation given in the answer to ITQ 9, and termed these structures *transform faults*. He called them transforms because, although they show great lateral displacements, they terminate abruptly at both ends, and are transformed into a different structure—an ocean ridge (as in the case illustrated in Figure 39), an island arc, or a mountain belt.

transform faults

A good example of one structure transforming into another can be seen in the Western Pacific. Look at the *World Ocean Floor* chart; locate the Fiji Islands to the north of New Zealand. To the west lies the New Hebrides Trench, and to the east the Kermadec-Tonga Trench. The two trenches are linked by a transform fault; the New Hebrides Trench is transformed into the fault, and to the east the fault is transformed back into a trench.

Confirmation of the existence of this new class of faults was first announced in 1966 by earthquake first-motion studies (see Figure 8, Unit 4) along the faults, made possible by the world-wide network of standardized seismographs that had been set up for the International Geophysical Year in 1957–8. Analyses of seismic shocks emanating from Wilson's postulated transform faults show the movements that would be expected from opposing directions of sea-floor spreading, rather than those suggested by the offsets of the ocean ridges. So, as well as supporting the transform fault hypothesis, the earthquake data provided yet more support for the sea-floor spreading hypothesis.

4.10 Global tectonics

From 1966 onwards there was a veritable explosion of papers describing the existence of sea-floor magnetic anomaly profiles that confirmed the Vine and Matthews hypothesis. In 1966 Vine published a paper, 'Spreading of the ocean floor; new evidence', whose title no longer coyly concealed the sea-floor spreading ideas as his 1963 paper with Matthews had done (that was given the innocent heading 'Magnetic anomalies over ocean ridges'). Thus in less than five years the climate of scientific opinion had completely changed from sceptism to enthusiasm. And, while more evidence poured in from the oceans, other workers showed how the concept of sea-floor spreading could be extended to explain most of the major features of the Earth's crust.

In 1967, D. P. McKenzie and R. L. Parker (both ex-Cambridge geophysicists) then working at the University of California at San Diego, published a paper in *Nature* entitled 'The North Pacific: an example of tectonics on a sphere'. They suggested that data concerning sea-floor spreading, transform faults and island arcs could be explained 'if the sea-floor spreads as a rigid plate, and interacts with other plates in seismically active regions ...'. They suggested that the rigid plates are aseismic areas (that is, they show virtually no seismic activity) and that they move like paving stones on the surface of a sphere.

The following year, W. Jason Morgan of Princeton University published a paper entitled 'Rises, trenches, great faults and crustal blocks'. He suggested what he called 'a geometrical framework with which to describe present-day continental drift'. His approach was an extension of Tuzo Wilson's transform fault concept applied to a spherical surface. He envisaged that the surface of the Earth is divided into about 20 blocks:

> Some of these blocks are of continental dimensions (the Pacific block and the African block); some are of sub-continental dimensions (the Juan da Fuca block, the Caribbean block, and the Persian block). The boundaries between the blocks are of three types and are determined by present day tectonic activity*. The first boundary is the rise** type at which new crustal material is being formed. The second boundary is the trench type at which crustal surface is being destroyed ... The third boundary is the fault type at which crustal surface is neither created or destroyed.

Today, these three types of block boundaries, or *plate boundaries*, are termed:

1 constructive boundaries;

2 destructive boundaries;

3 conservative boundaries.

We shall return to a detailed discussion of these in Section 5, but first we need to give more attention to the idea of *lithospheric plates moving on the surface of a sphere*—this was one of the most significant points made by Morgan in his 1968 paper. He discussed how this movement could be described by reference to a *pole of rotation*. This concept is described in Figure 40, and is illustrated also in TV 07.

* *tectonic activity*: meaning large scale crustal movements.

** ocean *rise* and *ridge* have the same meaning.

Examine the *World Ocean Floor* chart and Figure 40. Do you think the general trend of segments of the Mid-Atlantic Ridge between fracture zones is parallel to:

(a) the flanking coastlines?
(b) a small circle about a pole of spreading?
(c) a great circle passing through a pole of spreading?

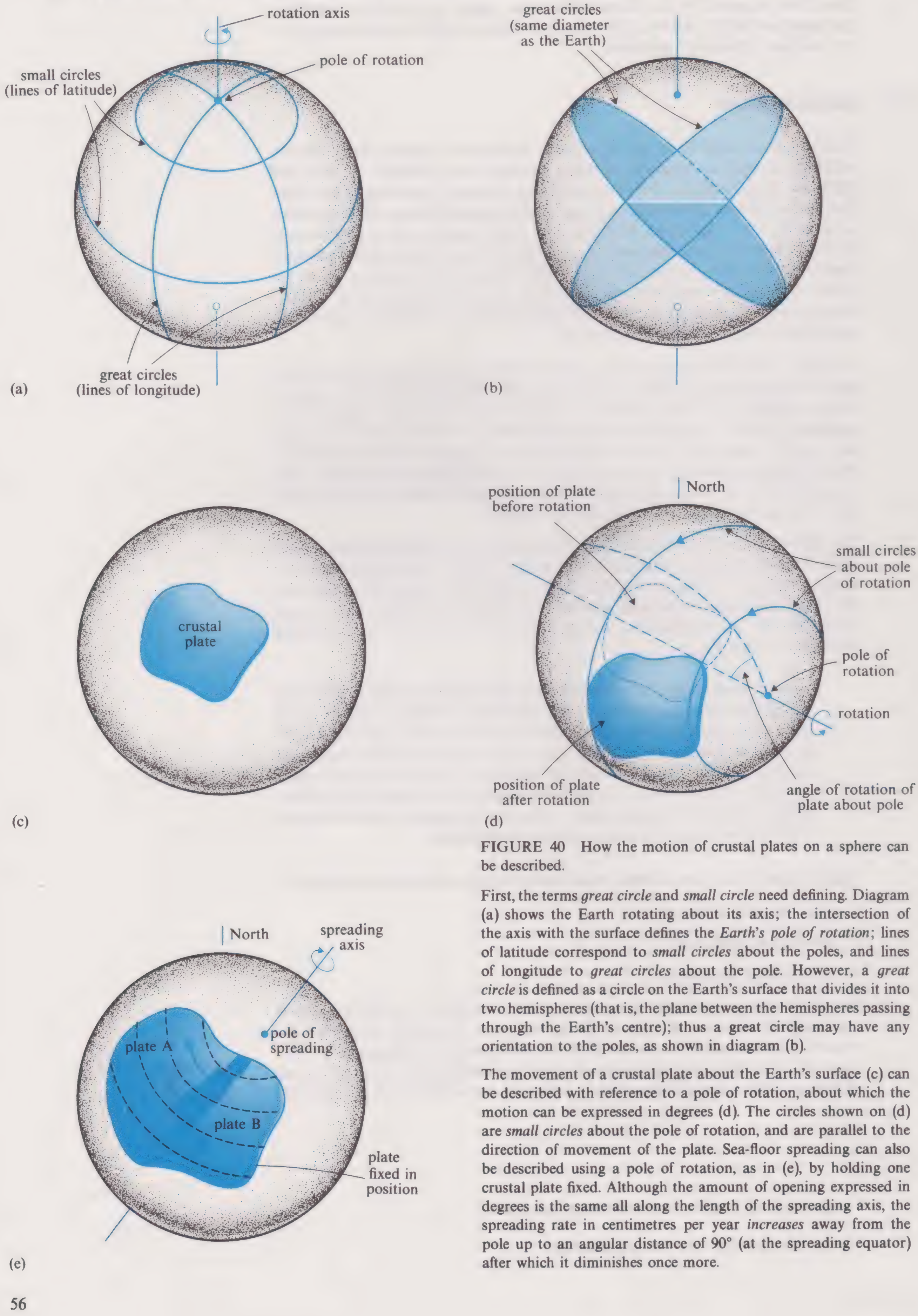


FIGURE 40 How the motion of crustal plates on a sphere can be described.

First, the terms *great circle* and *small circle* need defining. Diagram (a) shows the Earth rotating about its axis; the intersection of the axis with the surface defines the *Earth's pole of rotation*; lines of latitude correspond to *small circles* about the poles, and lines of longitude to *great circles* about the pole. However, a *great circle* is defined as a circle on the Earth's surface that divides it into two hemispheres (that is, the plane between the hemispheres passing through the Earth's centre); thus a great circle may have any orientation to the poles, as shown in diagram (b).

The movement of a crustal plate about the Earth's surface (c) can be described with reference to a pole of rotation, about which the motion can be expressed in degrees (d). The circles shown on (d) are *small circles* about the pole of rotation, and are parallel to the direction of movement of the plate. Sea-floor spreading can also be described using a pole of rotation, as in (e), by holding one crustal plate fixed. Although the amount of opening expressed in degrees is the same all along the length of the spreading axis, the spreading rate in centimetres per year *increases* away from the pole up to an angular distance of 90° (at the spreading equator) after which it diminishes once more.

The segments of the ridge between fracture zones approximate to *great circles* through the pole of spreading (compare with Figure 40e). If you look carefully at the *World Ocean Floor* chart, you will see that (a) is incorrect although superficially the whole ridge looks as though it parallels the adjacent coastlines because it is always approximately equidistant between them. Answer (b) is obviously incorrect; look again at Figure 40e.

Morgan showed that, by drawing great circles perpendicular to the trends of the transform faults that offset the Mid-Atlantic Ridge in equatorial regions, the pole of rotation for the African and South American crustal plates could be located. In other words, the transform faults and associated fracture zones follow *small circles* about the rotation pole/spreading pole. This is explained in Figure 41. However, it is a phenomenon easier to demonstrate on a sphere than by using the *World Ocean Floor* chart, and so it is demonstrated in TV 07.

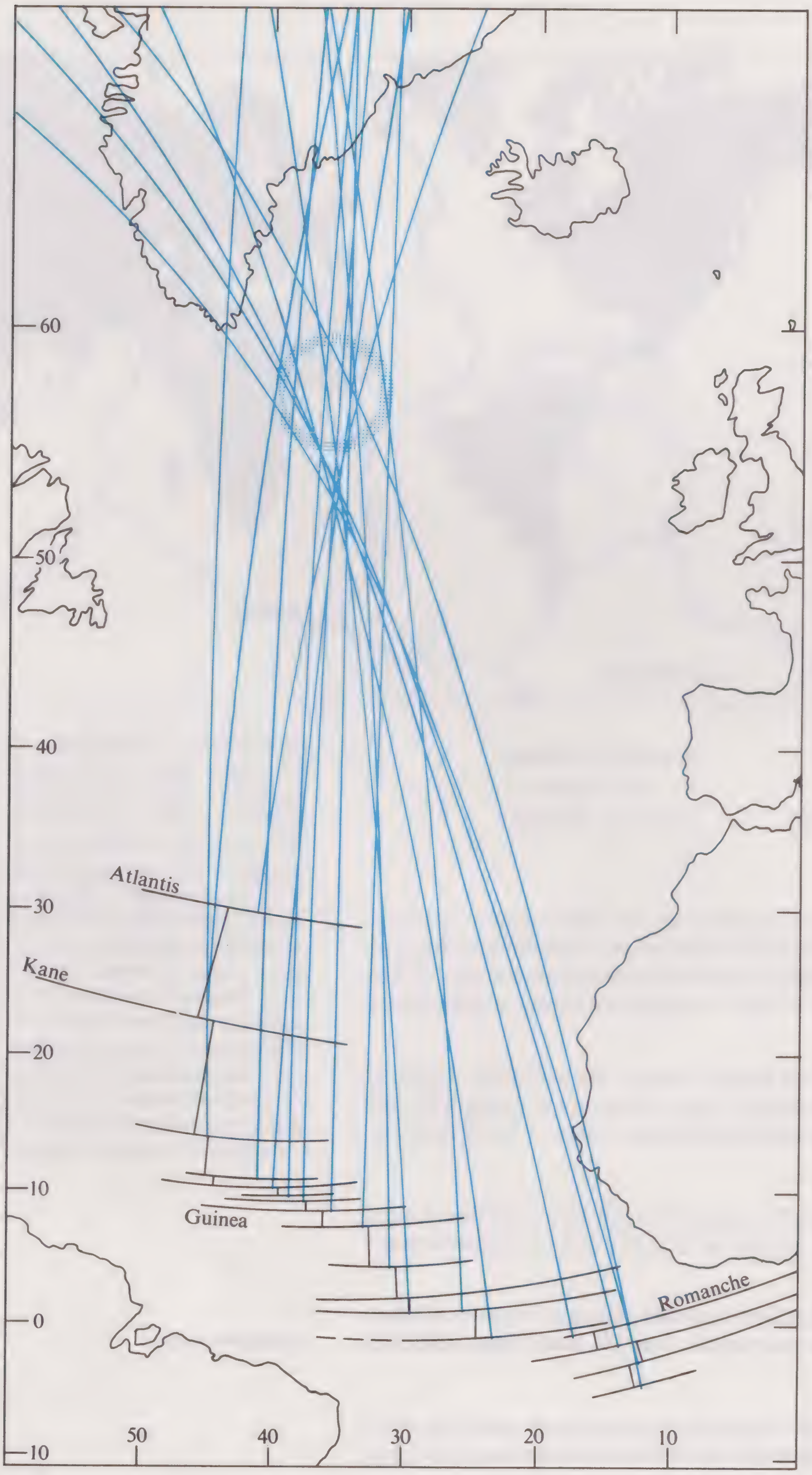


FIGURE 41 The pole of rotation for the African and South American crustal blocks located by drawing great circles perpendicular to equatorial Atlantic fracture zones. With one exception, all the lines pass within the circle shown.

This analysis of the movements of crustal blocks around the surface of a sphere—spherical geometry—involves sophisticated trigonometry which need not concern us. However, you should have grasped the basic principles that underly it (summarized in Figures 40 and 41), and realize that it is a powerful tool for integrating data concerning plate movements. Several such integrations were published in 1968, as well as that by Morgan. Xavier Le Pichon, a French oceanographer then working at the Lamont Geological Observatory in New York State, published a paper that extended Morgan's analysis to include a comprehensive survey of all sea-floor magnetic anomaly data, and the location of oceanic fracture zones that were known at that time. His model was reduced to *six* major rigid blocks, and on it he showed the rate of differential movement he had calculated on the basis of known rates of sea-floor spreading and the location of the rotation poles for each block. An up-to-date version of this map is shown in Figure 42.

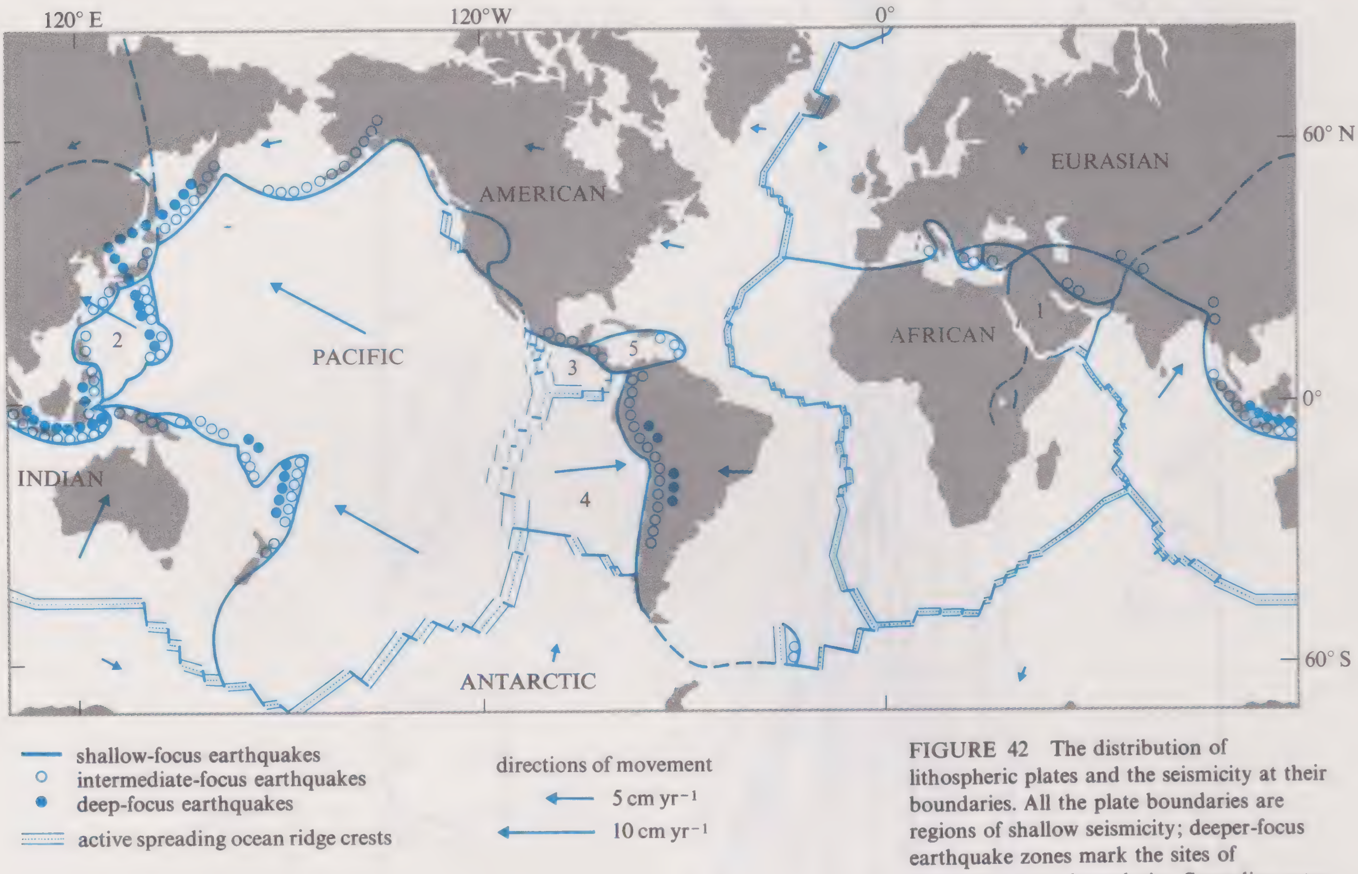


FIGURE 42 The distribution of lithospheric plates and the seismicity at their boundaries. All the plate boundaries are regions of shallow seismicity; deeper-focus earthquake zones mark the sites of destructive plate boundaries. Spreading rates at constructive plate boundaries are shown schematically by the width between the parallel lines used to show them. The six major plates are named. The directions of plate movement are shown by arrows, the lengths of which are proportional to the rate of movement. These plate motion directions have been calculated by assuming that the African plate remains stationary. Minor plates are numbered as follows: 1 Arabian; 2 Philippine; 3 Cocos; 4 Nazca.

Figure 42 shows South America flanked by two ocean ridges, which, as you read earlier, are both spreading at rates of several centimetres per year. But these two spreading centres are spreading towards each other. Do you remember Hess's speculation on how this apparent excess of crust formation was accommodated?

He suggested that oceanic crust plunges beneath the continents. Figure 42 shows that the South American and Nazca Plates are colliding with each other along the region of the trench off the west coast of South America.

Do you remember what Benioff zones are? (If not, turn to Section 4.4 and refresh your memory). How do they fit into this picture of crustal plates growing and colliding?

These inclined zones of earthquakes mark the sites at which slabs of ocean crust are plunging down into the mantle; they are often called *subduction zones*.

subduction zones

Just as the existence of the new class of geological faults, namely transform faults, had been confirmed by first-motion studies of earthquakes with epicentres along

their length, so was the concept that blocks of crust were jostling each other on the surface of a sphere. Yet another 1968 paper, also from Lamont, written by Bryan Isacks, Jack Oliver and Lynn Sykes, gave strong support to what they termed the 'new global tectonics' (now generally called *plate tectonics*).

Their interpretation, based on a global analysis of earthquake first-motion directions, confirmed Le Pichon's view of the movements of the six major blocks. Moreover, the three authors added a third dimension, namely depth, and showed that the earthquake data confirmed the view that ocean crust was indeed plunging downward (was being subducted) along Benioff zones, confirming the interpretation based on earthquake epicentre depths, gravity anomalies and heat-flow measurements.

Thus, by 1968, a wide variety of geological and geophysical observations had been integrated into one global theory, that of plate tectonics. In Section 5 of these Units we shall outline in more detail some of the processes that occur where plates are formed, and where they collide.

4.10.1 Objectives of Section 4.10

You should now be able to:

(a) Describe the plate tectonic hypothesis (this will be elaborated in Section 5.1). (SAQ 13)

(b) Describe the evidence that favours the plate tectonic hypothesis (SAQ 14):

(i) seismic zones and first-motion studies of earthquakes;
(ii) geometry of spreading centres and transform faults;
(iii) poles of plate rotation and spreading.

Before reading on, complete SAQs 13 and 14.

SAQ 13 (*Objective (a)*) Complete the blanks in the following description of plate tectonics:

Ocean floor is envisaged as continuously accreting to a ..... (a) plate which is ..... (b) inactive, and which interacts with other plates along active zones of ..... (c) and seismicity. The movement of the plates over the surface of a ..... (d) can be described with reference to a ..... (e) of rotation. ..... (f) faults trend along the direction of ..... (g) circles about the ..... (e) of rotation, whereas oceanic ridges between these faults trend along ..... (h) circles passing through the ..... (e). There are three types of plate boundaries:

1 .... (i) (do not worry if you list these in a
2 .... (j) different order to those given in the
3 .... (k) answer)

Along the first type, new ..... (l) is formed by ..... (m). Along the second type, oceanic crust and upper mantle is being ..... (n).

SAQ 14 (*Objective (b)*) Consider the list of topics we have considered in these Units:

A Deep-sea drilling results
B Palaeoclimatic data
C Palaeomagnetic data
D Ocean-floor magnetic anomalies
E Fit of the topography of continental margins
F Earthquake first-motion studies
G Magnetic polarity reversal timetable

Match these topics with those of the following concepts to which they contributed in a major way:

1 Continental drift (choose three items)
2 Sea-floor spreading (choose three items)
3 Transform faults (choose three items)
4 Plate tectonics (choose one item only)

5 Plate tectonics: a summary

5.1 Introduction and revision

Many of the features discussed in Section 3, and a few of those outlined in Section 4, were known to geologists working 30 years ago, but they were not able to explain them all in terms of a single hypothesis concerning the workings of the Earth's outer skin. As we saw in the last Section, it was only when the nature of the ocean floors and underlying crust became better known that a truly global hypothesis emerged. This global theory, plate tectonics, is so elegantly simple that students find it easy to recall its basic details, but often forget the *evidence* that supports the theory. We hope that the approach we have adopted in these Units will ensure that you have a thorough grasp of the evidence that supports the concept of plate tectonics.

You should by now have a very generalized picture in your mind's eye of the fundamental aspects of plate tectonics, as illustrated in Figure 43.

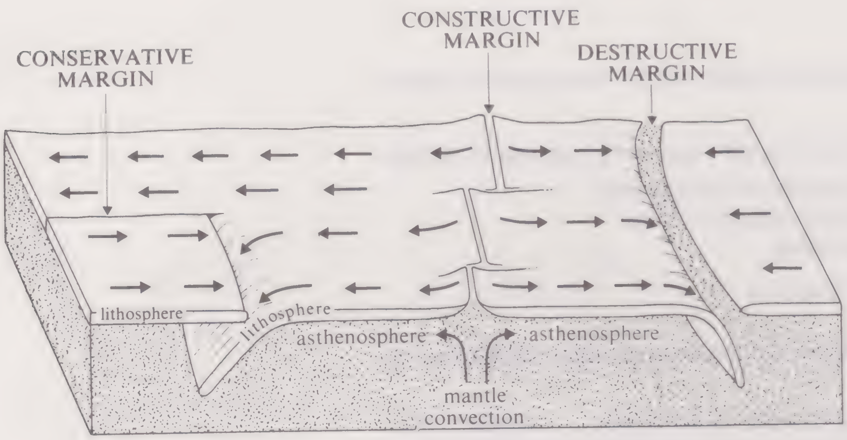


FIGURE 43 Diagram showing the basic concept of plate tectonics. Plates of rigid lithosphere (which includes the crust and uppermost mantle) about 100 km thick overly a layer of relatively low strength (considered over long periods of time). Mantle material rises beneath *constructive margins* (ocean ridges), and plate material plunges back into the mantle at *destructive margins*. Along a third type of margin, crustal plates slide past each other, forming *conservative margins*.

Figure 44 adds some realism to this concept, depicting Africa and South America as part of two separate crustal plates.

Which of the boundaries (marked A–A′, B–B′, C–C′) is:

(a) a constructive plate margin?

(b) a destructive plate margin?

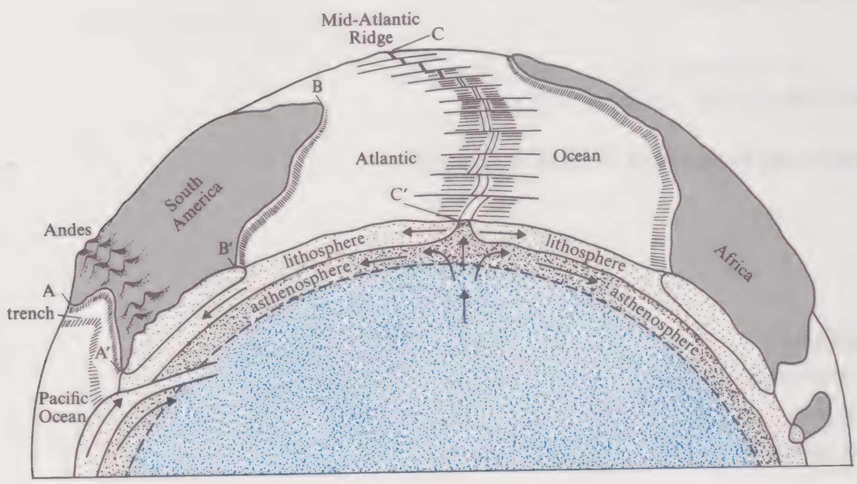


FIGURE 44 Diagram showing the relationships between three crustal plates, the African, South American, and Nazca plates.

A–A′ is a destructive margin; C–C′ a constructive margin. B–B′ is neither, for it is in the middle of a plate, but this type of continental margin is termed a passive continental margin. If you examine the *World Ocean Floor* chart, you will see that much of the Atlantic Ocean is flanked by such margins, in contrast to the Pacific, which is ringed by active continental margins (which coincide with destructive plate margins).

In Section 4, we made no concerted attempt to relate the work you did when studying Figures 7–11 to plate tectonics. You should be able to remedy this omission now by completing ITQs 10 and 11. To answer these questions, you will need to study Figures 7–11 (pp. 82–3) and the *World Ocean Floor* chart once more.

ITQ 10 Figure 45 shows the boundaries between the major plates, but does not distinguish whether they are destructive or constructive plate margins.

Identify whether these plate margins are destructive or constructive by drawing in the symbols given in the key to the map. Name the plates in the spaces provided.

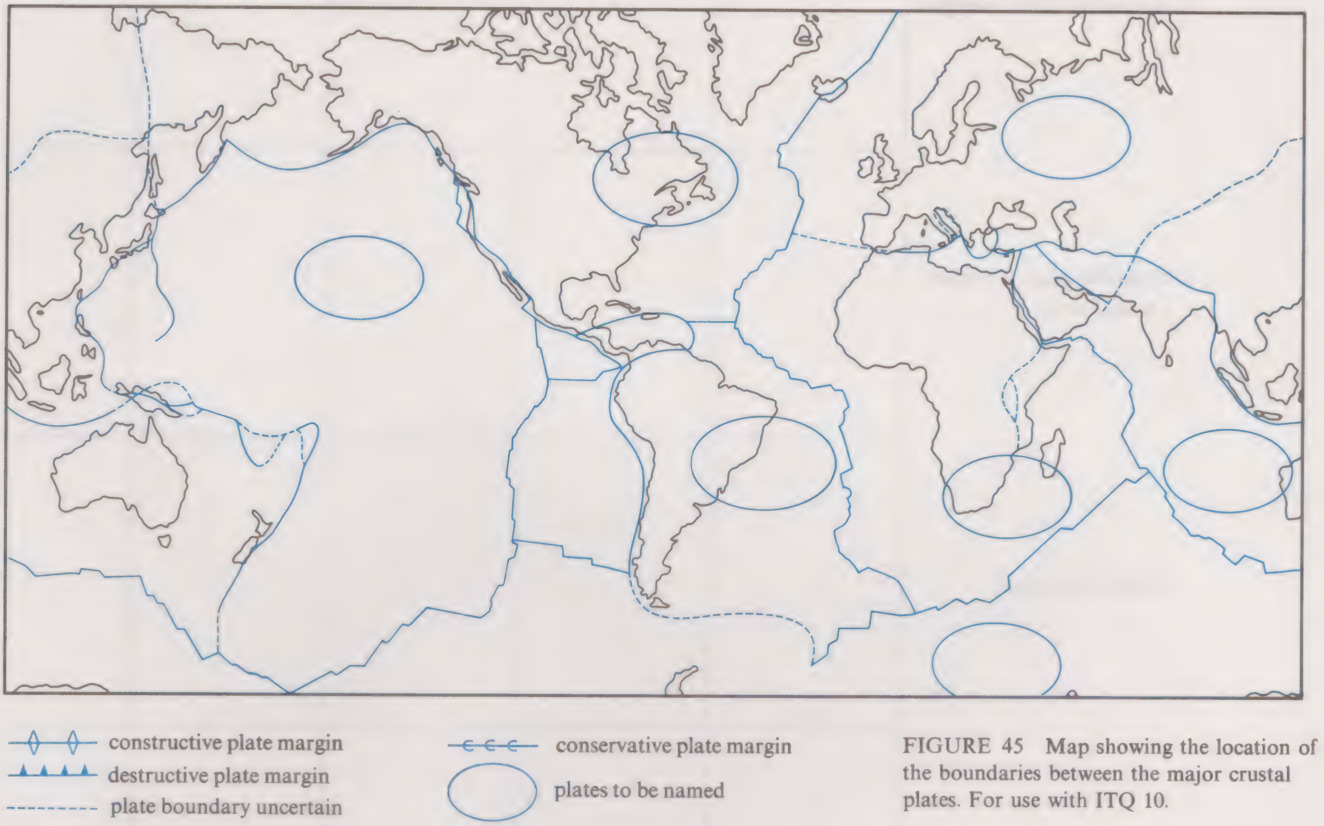


FIGURE 45 Map showing the location of the boundaries between the major crustal plates. For use with ITQ 10.

ITQ 11 Complete Table 4 (overleaf) to describe the main features of constructive and destructive margins. In the latter case, distinguish between such boundaries involving adjacent oceanic plates (e.g. island arcs in the Western Pacific), adjacent oceanic and continental plates (e.g. the Andean region) and adjacent continental plates (e.g. the Himalayas). In addition, the table has space for the features of mid-plate regions to be summarized.

Once you have answered ITQs 10 and 11 (and checked your results with those on page 78) you will be well briefed to read the succeeding Sections, which outline the geological processes and resultant rock types and structures that occur at each type of plate margin. At this stage in the Course we can give only an elementary description, for we have yet to discuss in detail any of the processes that contribute to the formation of igneous, sedimentary and metamorphic rocks*. These will be treated in Unit 27 and related to the plate tectonic model.

Figure 42 (p. 58) is a map showing the major lithospheric plates of the Earth and the nature of the seismic activity at their boundaries. This map is rather deceptive, as it does not show the relationships between the plates in polar regions; indeed, it is much easier to see the way the plates interact with each other on a globe, as shown in TV 07.

* See footnote on page 43 for explanation.

TABLE 4 For use with ITQ 11.

	Topography (name the features present)	Age of rocks (0–10 Ma, 10–100 Ma, or >1 000 Ma)	Seismic activity (shallow-, intermediate- or deep-focus)	Volcanic activity (effusive or explosive)	Other notable features, such as heat flow (high, average, low) or gravity anomalies
Constructive plate margins					
Destructive plate margins Ocean/ocean					
Ocean/continent					
Continent/continent					
Mid-plate regions Continental					
Oceanic					

5.2 Constructive plate margins

Study comment Do not worry if you cannot fully understand this Section. Its purpose is to relate some of the rock specimens you have in your Home Experiment Kit (S3 basalt; S4 peridotite; S5 gabbro) to the processes thought to operate at constructive plate margins. Given that such processes are responsible for the formation of some 70 per cent of the Earth's surface area, they deserve some attention. However, at this point in the Course, you are not expected to answer continuous assessment items related to this Section, for the topics introduced here are treated in more detail in Unit 27.

Oceanic crust covers about 70 per cent of the Earth's surface, and as already shown in Figure 28 on page 41, it has a remarkably simple layered structure. How is this crust generated in such a uniform way?

Figure 46* summarizes the main features of constructive plate boundaries. It must be stressed that this is a hypothetical model, based both on investigations of ocean ridges and on studies of slices of presumed oceanic crust that have been thrust up into continental regions. At the time of writing, deep-sea drilling has penetrated only to a depth of 600 metres into oceanic crust.

Figure 46a shows the ocean ridge sited over the rising limbs of two mantle convection cells. Mantle material is shown rising under the ridge, 'filling the gap' as the two plates move away from each other, and by so doing, actually grow. But what is the *process* by which they grow? And how is the characteristic layered structure (shown in Figure 28 and the left-hand side of Figure 46b) of oceanic crust produced? Before speculating on the processes that might be operating beneath ocean ridges, a little more must be said about the nature of the layers.

Deep-sea drilling has only penetrated layer 1, and a little way into layer 2. Layer 1 consists of sedimentary rocks, formed either from the dead remains of organisms living in the surface waters of the ocean, or from chemical precipitates on the sea bottom, such as manganese nodules (see Figure 46c). Layer 1 may also contain volcanic ash that has settled out through the ocean water, but is remarkable for its lack of sedimentary particles derived from continental crust.

Why do you think layer 1 thins and becomes absent towards the ridge crest shown in Figure 46b?

Sediment only starts to accumulate after oceanic crust has formed (that is, layer 2 and below). As the crust is youngest over the ridge crest, and oldest on the flanks (on the edge of the diagram), sediment has obviously accumulated for a longer period over crust that has now moved away from the spreading centre. This thickening of layer 1 away from ridge crests is well documented by numerous seismic surveys and Deep-Sea Drilling Project sites.

Layer 2 has a fairly uniform thickness of just under 2 km, and is exposed in the vicinity of ocean ridges. Here, its surface is seen to consist of basalt pillow lavas (the pillow shape is characteristic of lavas formed underwater; see Figure 46d), and deep-sea drilling confirms the view that the whole of layer 2 is largely composed of such lavas.

Studies of rocks now exposed on continents, but believed to represent oceanic crust, suggest that layer 3 can be divided into two parts. The upper part is probably formed of vertical sheets of igneous rock, again of basaltic composition, known as *dykes* (see Figure 46e). The structure of this layer is analogous to that of a pack of cards stood vertically, each card representing a single dyke. It indicates that the crust was experiencing *extension*. The upper boundary of the dykes with the lavas of layer 2 is not abrupt, for some dykes penetrate the lavas. The lower half of layer 3 consists of *gabbro*, a rock with the same chemical and mineral composition as basalt, but with a larger crystal size (the gabbro is specimen S5 in your collection).

* Figure 46 is on the next two pages.

If the chemical and mineral compositions of *basalt* and *gabbro* are the same, what is the reason for their different crystal sizes (recall Audio-vision sequence, 'Rock specimens', associated with Unit 4)?

The larger crystal size of the gabbro is due to the fact that it cooled more slowly than basalt. In the crustal environment we are discussing, this is hardly surprising, as the gabbros must have formed several kilometres below the basaltic lavas.

It is possible that the upper part of the gabbros of layer 3 are uniform in structure, in contrast to a layered base (see Figure 46f; we shall return to the significance of this later).

The base of layer 3 is of course marked by a seismic discontinuity—the Moho. Layer 4 is generally agreed to be composed of *peridotite* (Specimen S4) which has a greater density than gabbro or basalt. The top kilometre or so of layer 4 is thought to be composed of *layered peridotite* (the layering being similar to that shown in Figure 46f).

FIGURE 46 The features and processes characteristic of constructive plate boundaries (see the text for full discussion).

(a) Block diagram of the crust and mantle beneath a spreading axis (ocean ridge).

(b) Enlargement of part of (a) showing an interpretation of the crustal and mantle processes operative during sea-floor spreading, and the nature of the layers produced.

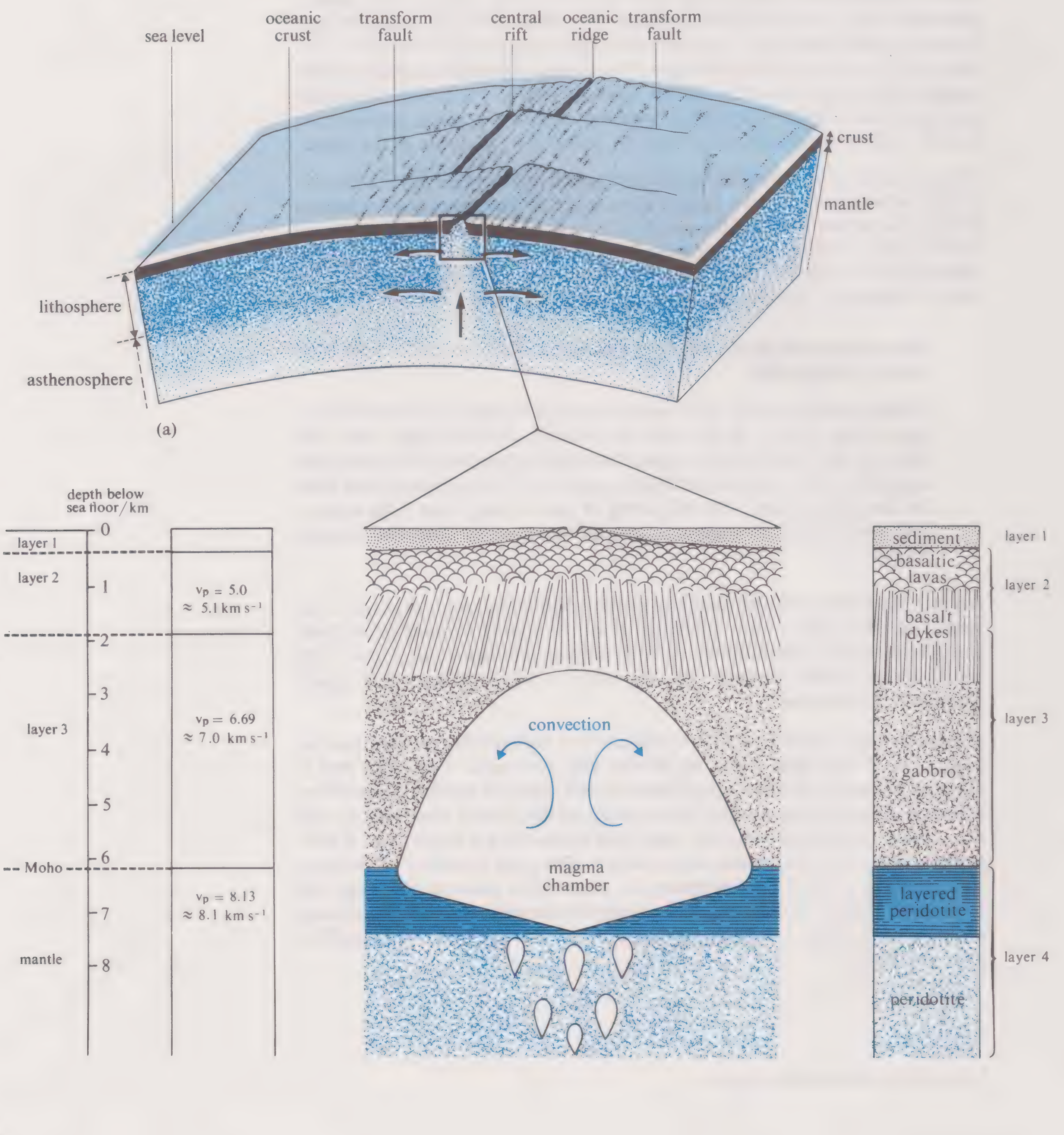
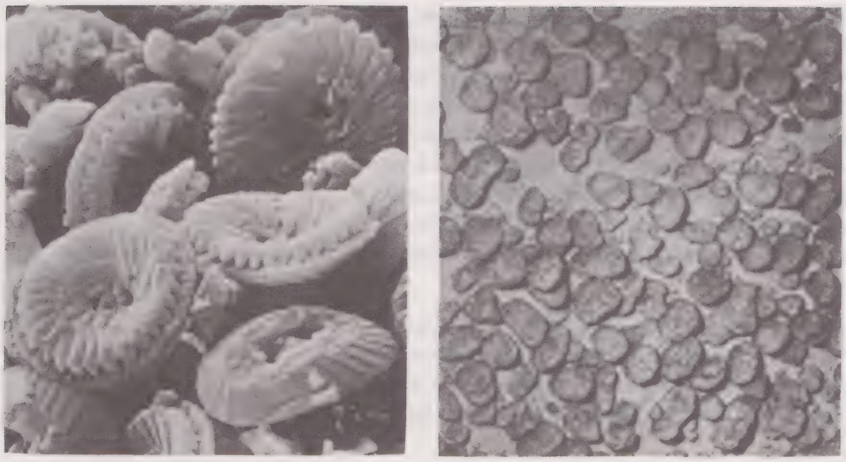


FIGURE 46 continued.



(c) *Layer 1*: deep-sea sediments; left: a calcareous ooze produced by microscopic organisms that live in ocean surface waters and that fall to the bottom after their death (average diameter a few thousandths of a millimetre); right: manganese nodules (average diameter 6 cm).

(d) *Layer 2*: basaltic (see specimen S3) pillow lavas extruded onto the ocean floor along oceanic ridges*.

(e) *Layer 3*: vertical sheets of basaltic rock (known as dykes)*.

(f) *Layer 4*: a coarse-grained igneous rock with the same chemical and mineral composition as basalt (it is known as a *gabbro* (specimen S5)) showing a layered structure*.

* These examples are taken from exposures of rocks believed to be oceanic crust that has been thrust up into continental regions.

The kind of rock sequence described above can be seen in continental regions in many parts of the world. All these examples occur in regions interpreted as ancient destructive plate margins in which slices of oceanic crust, instead of being subducted *down* into the mantle, have been thrust *upwards* onto continental crust. Small samples of the association of basaltic lavas and dykes, gabbros and peridotites occur in Britain (for example, in the Lizard Peninsula in Cornwall, Lleyn Peninsula and Anglesey in North Wales, and in Southern Scotland). What kind of igneous process could form the rock sequence just described? Any hypothesis must not only account for this sequence, but also the uniform thickness of layer 3, and of course for sea-floor spreading itself!

Figure 46b shows a large chamber filled with liquid rock of basaltic composition (*magma*). The existence of this body of liquid is postulated both because P-wave velocities beneath ocean ridges are anomalous (lower than in normal mantle), and because it is a model that can produce the layered structure we have been examining.

> What would happen to any crystals that solidified from the liquid, bearing in mind that experimental results suggest that the first crystals to appear have a greater density than the liquid that surrounds them?
>
> Such crystals would sink to the bottom of the chamber.

It is thought that these crystals sinking to the bottom of the magma chamber account for the densest layer of peridotite accumulating at the bottom of the chamber. Layering in both the peridotite and the gabbros is produced by convection currents within the chamber, which at times may prevent all but the densest crystals settling. During periods when there is no convection, crystals of all densities will settle, and so layers of different density are produced. The uniform gabbro is produced by steady crystallization on the walls of the chamber, so that away from the region beneath the ridge crest the magma is totally solidified. Above the chamber, magma is constantly being forced upwards to form dykes, which in turn 'feed' the outpourings of lava on the ocean floor. The dykes continually 'shoulder apart' their predecessors, much as an extra playing card might be forced up into the vertical stack of cards we imagined earlier. Whether this 'shouldering apart' is the driving force behind sea-floor spreading, or whether the dykes are filling spaces left as the ocean ridge region is pulled apart is still uncertain, as we shall see in Section 5.4.

Finally, why are there ocean ridges over rising convection currents, and why is the topography of these regions so rugged? The answer to both questions relates to the fact that the region is one of high heat flow. Because this part of the crust is hotter, it is less dense, and so it stands higher than the surrounding regions. As the newly formed crustal material moves away from the spreading centre, it cools, and so its elevation decreases, the drop in height being accommodated along faults running parallel to the ocean ridge, thus accounting for the characteristic 'grain' of the topography depicted on the *World Ocean Floor* chart.

5.3 Destructive plate margins

Figure 47* shows the main features of margins of this type. The great variety of complex igneous, sedimentary and metamorphic processes that occur on these margins will be discussed in Unit 27.

Ocean/continent and ocean/ocean destructive margins have a number of features in common (see Figures 47b, 47c and 47d):

1 subduction of oceanic crustal material is revealed by an inclined zone of earthquakes (Benioff zones), which are generally steeper beneath ocean/ocean margins;

2 explosive volcanic activity;

* Figure 47 is on pages 68 and 69.

3 ocean trenches;

4 negative gravity anomalies over the trenches, positive gravity anomalies over island arcs or mountain ranges.

Why do you think oceanic crust nearly always dives beneath continental crust at destructive plate margins?

Because oceanic crust is denser than continental crust.

Given that one plate is sliding beneath another at destructive plate margins, what is the source of heat that generates the liquid rock that feeds the volcanic activity in these regions?

Friction between the two plates generates liquid rock (magma). Melting also occurs as the down-going plate descends into hotter regions at depth. The resultant igneous activity is largely responsible for building up the island arcs on previously existing oceanic crust (see Figure 47b, p. 68).

Would you expect the types of volcanic rock in ocean/ocean and ocean/continent continental margins to be the same, or different? Look carefully at Figures 47b and 47c, and bear in mind that in 47b rocks of basaltic composition dominate each plate whereas in 47c rocks of basaltic and granitic composition are involved.

Not surprisingly, basaltic rocks dominate the island-arc volcanic environments, but the Andean-type destructive margins are dominated by volcanic lavas intermediate in composition between basalt and granite—these are known as *andesites* (named, of course, after the Andes). This intermediate composition is characteristic of continental crust as a whole; only its upper part has a granitic composition. However, andesites are formed beneath island arcs, as will be discussed in more detail in Unit 27.

Ocean/continent margins are also characterized by the occurrence of large intrusive masses of granite, produced by the melting of the plates along subduction zones. Specimen S1 in your Home Experiment Kit came from one such intrusive mass. The granitic magma, being lighter than the surrounding rocks, moves upwards in the crust, and may reach within a few kilometres of the surface. There it solidifies to form huge elongate masses of granite called *batholiths* which may later be exposed at the surface once the overlying rock cover is removed.

Continental rocks may be crumpled and metamorphosed at destructive margins; details of these processes are discussed in second-level Earth science Courses.

Sediments accumulate in the ocean trenches associated with the two types of destructive margin, and their composition will be different in the two types of plate margin, because only in margins of Andean type are fragments of continental rock swept into the trenches. In both margins, the sediments accumulating in the trenches may eventually be carried down the subduction zone, and be 'plastered' onto either the island arc, or continental crust.

Continent/continent destructive plate margins are a hybrid type of margin, because the two slabs of continental crust that eventually collide first evolve either as passive or destructive continental margins (see Figure 47f); for example, whereas the Himalayan region today shows no volcanic activity, the sequence of rocks within it shows evidence of its former existence as an ocean/continent plate.

The assemblages of rocks and structures produced at destructive margins, and their arrangement in long linear or curved belts provides a means of recognizing 'fossil' plate boundaries. In Britain, the granites of Devon and Cornwall mark a subduction zone that existed some 300 Ma ago, and those in Southern Scotland record plate collision even further back in time, around 450 Ma ago. Similarly, great thicknesses of volcanic and sedimentary rocks in North Wales and the Lake District suggest that these regions were the sites of island arcs between 500 and 400 Ma ago.

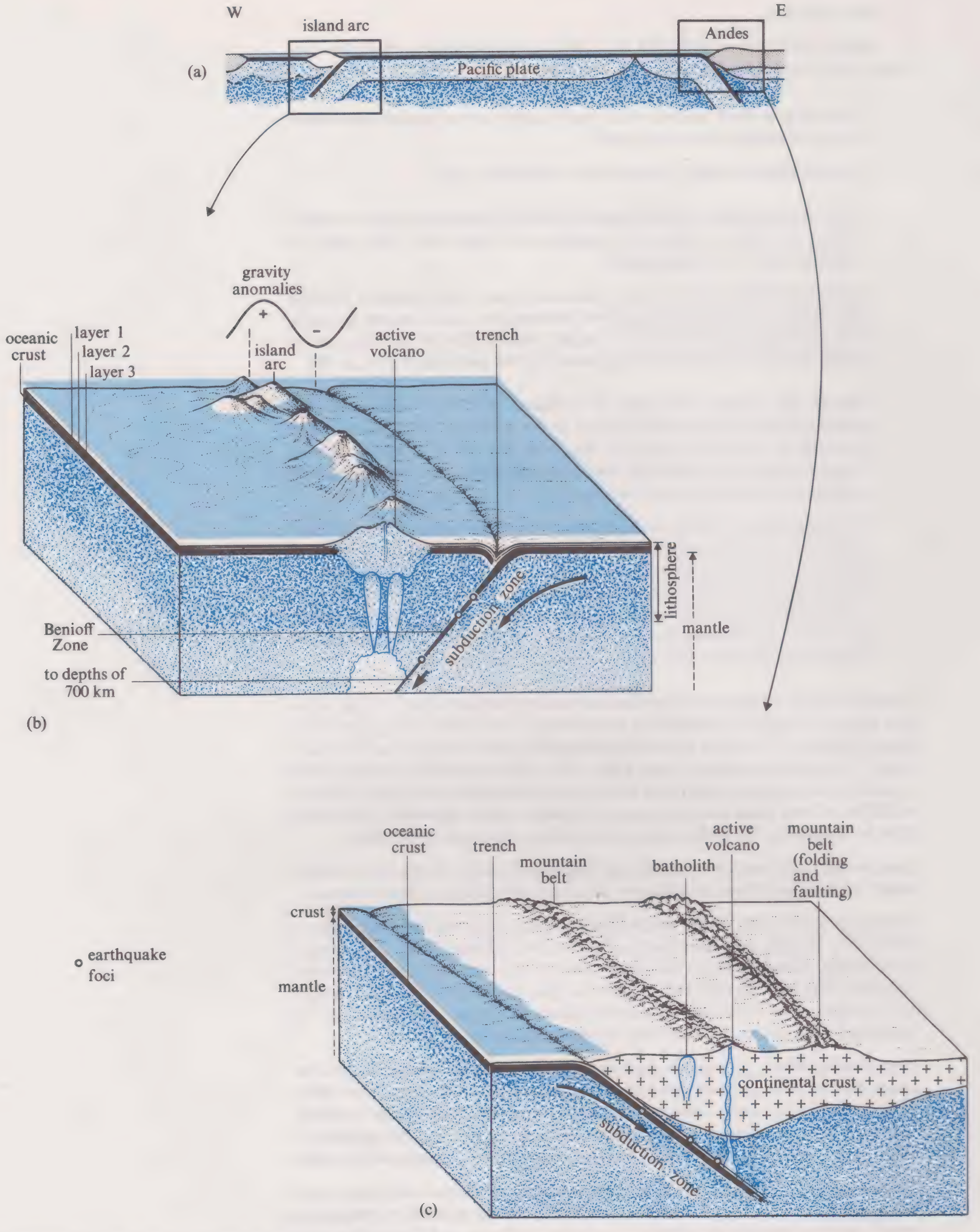


FIGURE 47 The features of the three types of destructive plate margin.

(a) East–west sketch section across the Pacific Ocean, showing the location of ocean/ocean (island-arc type) and ocean/continent (Andean type) destructive plate margins.

(b) Block diagram showing the main features of an ocean/ocean (island-arc) destructive margin.

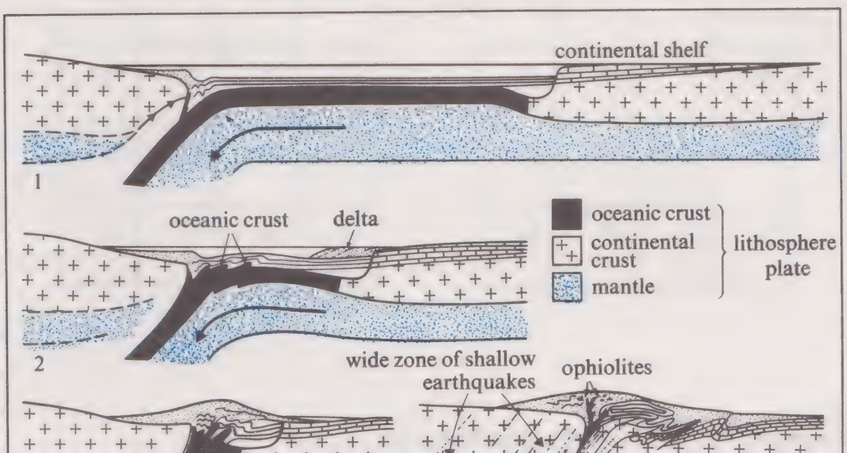
(c) Block diagram showing the main features of an ocean/continent (Andean) destructive margin.

(d)

FIGURE 47 (d) Typical Andean volcanic cone, consisting of a mixture of lava and volcanic ash, with the latter being the predominant component.

(e)

(e) Folded metamorphic rocks typical of the deeper parts of destructive margins, and indicating *compression* of the crust.



(f)

(f) Sequence of events leading to the formation of a continent/continent (Himalayan) destructive plate margin: 1 and 2: early stage, with passive *continental* margin converging on an ocean/continent destructive *plate* margin; 3 and 4: continent/continent destructive plate margin.

Note how slices of oceanic crust are caught up in the continental rocks and exposed at the surface as ophiolite complexes. Destructive plate boundaries of this type contain older relics of earlier, ocean/continent destructive margins, including volcanic activity. However, there is no such activity today in the Himalayan region.

5.3.1 Objectives of Section 5

Now that you have finished Sections 5.1–5.3, you should be able to:

(a) Draw on a map of the world the six major lithospheric plates, and indicate whether their boundaries are constructive or destructive (already tested by ITQ 11, page 61).

(b) Distinguish constructive and destructive plate margins on the basis of their rock types, contained structures and geophysical characters (SAQ 15).

SAQ 15 (*Objective* (*b*)) Select from the array below the characters of the three types of plate margin identified on the three blank arrays. Put a tick in the appropriate boxes to indicate your choices.

1 Positive gravity anomaly over depressed region	2 Basaltic volcanic activity	3 Narrow zones of shallow-focus earthquakes	4 Negative gravity anomaly over depressed region
5 Island arcs	6 Large masses of granite (batholiths)	7 Metamorphism	8 Relatively low heat-flow values over depressed areas
9 Andesite volcanic activity	10 Broad seismic zone with earthquake foci lying along an inclined plane	11 Relatively high heat-flow values over elevated region	12 Uniformly layered crustal structure
13 Extensional features	14 Shallow- and intermediate-depth earthquakes in same region	15 Positive gravity anomaly over elevated region	16 Abundant basaltic dykes

Constructive margins

1	2	3	4
5	6	7	8
9	10	11	12
13	14	15	16

Destructive margins

ocean/ocean

1	2	3	4
5	6	7	8
9	10	11	12
13	14	15	16

ocean/continent

1	2	3	4
5	6	7	8
9	10	11	12
13	14	15	16

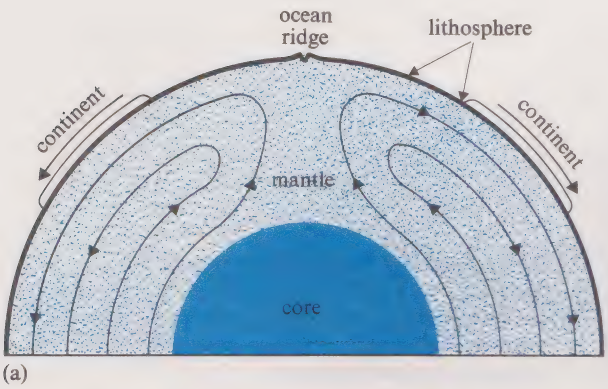
5.4 Causes of plate motion

Up to now we have described plate movement without attempting to discuss the mechanism that causes it, apart from mentioning that convection currents are likely to be involved. It is extremely difficult to find such a mechanism, because we are attempting to investigate something not only physically remote—buried deep in the Earth—but also remote in terms of its vast scale and the period of time during which it must have operated.

You will remember from Unit 4 that on seismic evidence the Earth's upper part is subdivided into the outer crust, separated from the underlying mantle by the Mohorovičić discontinuity. In the upper mantle there is a zone, extending from a depth of about 50 km below the Earth's surface to a depth of about 250 km, where seismic waves travel more slowly. This is called the seismic low-velocity layer. In Unit 4 it was suggested that in this layer the material of the Earth's mantle is sufficiently close to its melting temperature for about 5 per cent of it to be molten. The liquid is dispersed between the crystals that make up the layer; this gives a zone known as the *asthenosphere*, which is inherently weak. If the outer part of the Earth moves with respect to the inner part, then it may well do so along this layer. Similarly, isostatic adjustments may occur in this region too. *It is the outer part of the Earth (the lithosphere), incorporating both the crust and the uppermost part of the mantle above the low-velocity layer, that forms the moving plates.*

The plates appear to be passive passengers, and the driving mechanisms for their movement must therefore be located either in the asthenosphere or even deeper in the Earth. Various theoretical models have been constructed for this driving mechanism, based on attempts at calculating the rigidity, compressibility and plasticity of the Earth's interior.

The simplest model, proposed many years ago by Arthur Holmes, compared the Earth to a pan of boiling water in which convection currents have developed. The hotter water rises in the centre of the pan, spreads out at the surface, cools and descends down the sides of the pan. The model suggests that within the Earth there are huge convection currents rising under the ocean ridges and descending under the active plate margins, as shown in Figure 48a.



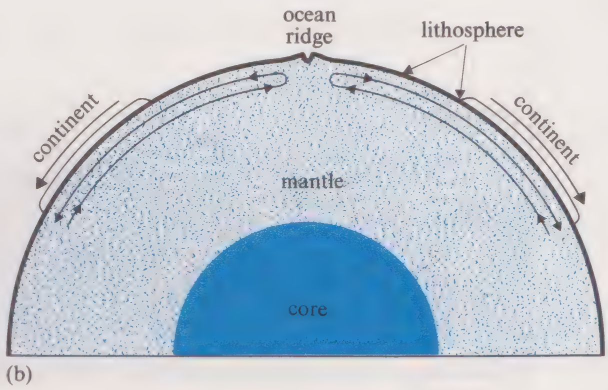
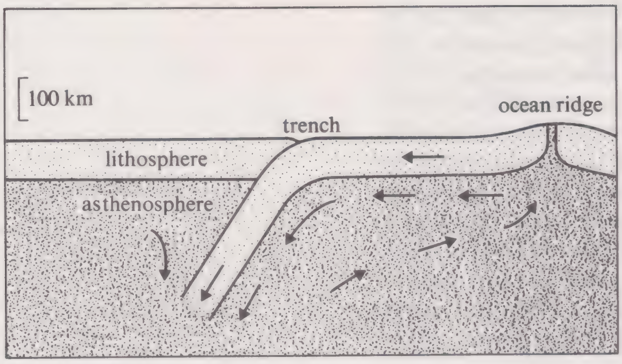


FIGURE 48 Convection current hypotheses.

(a) Convection current hypothesis involving the mantle, and accounting for the sites of ocean ridges and subduction zones.

(b) Modified convection current hypothesis involving long, flat convection cells within the Earth.

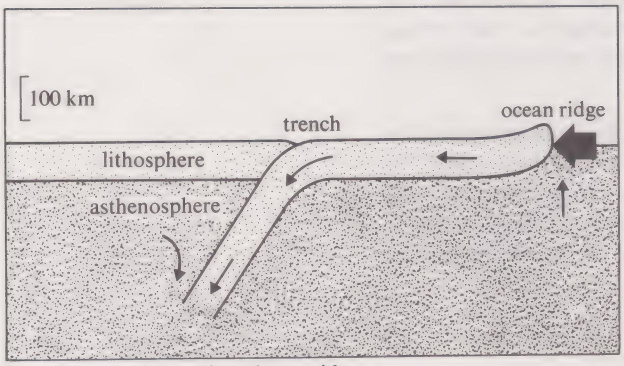
It has been suggested that the convection may take place within the thin layer of the asthenosphere, between 100 and 400 km deep (Figure 48b). This model has pancake-like convection cells, again rising under the ocean ridges but with the return current coming back only a few hundred kilometers below the outward-spreading, upper current. The whole problem really depends on just how fluid the asthenosphere really is. Does it have the 'stiffness' of treacle or of tar? Is it easily deformed? One hypothesis is that the layer is so well lubricated that, when a continental plate is ruptured and basaltic material is intruded into the lithosphere from the asthenosphere below, the mere injection of this new oceanic material causes the flanking continents to 'roll apart' (Figure 49b). Another suggestion is



(a) convection

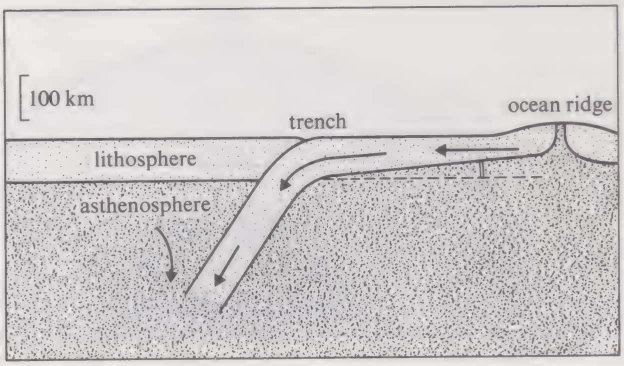
FIGURE 49 Alternative hypotheses to account for plate motion —or, which comes first, movement in the asthenosphere or plate motion?

(a) Convection in the upper mantle (asthenosphere) drags plates along. Sea-floor spreading fills the 'gap' thus created and ocean ridges are formed.



(b) lava injection pushes plates aside

(b) In this model, sea-floor spreading processes provide the 'push' at the constructive end of the plate. Molten rock rising at the ocean ridge shoves aside the two plates.



(c) gradient

(c) A gradient of 1/3 000 could be enough to cause plates to slide downhill at a rate of $4\,\mathrm{cm\,yr^{-1}}$, which, in turn, causes the upper mantle to flow. Ocean ridges are elevated areas because they are relatively hot. Again, sea-floor spreading fills the resultant gap between plates moving apart.

that as the ocean floor is highest at the ocean ridge axis, such a movement would be helped by the rigid plate sliding away from either side of the ridge simply under the influence of gravity (Figure 49c). Whatever the mechanism that starts plate motion, it is likely that there is a 'sinker effect' in which the relatively colder downgoing lithospheric plate, being also relatively denser than its surroundings, sinks still further into the hotter mantle.

So the details of plate motion are still sought! But the *cause* is almost universally accepted to be convection currents in the asthenosphere and upper mantle; all the models shown in Figure 49 depend on such an assumption. In Figure 49c the slope along which plates might slide is produced by thermal expansion over the rising limbs of convection cells, and the same rising limbs of convection cells in Figure 49b provide the source of magmas for the dykes that shoulder apart the plates.

6 A revolution in the Earth sciences

We cannot conclude the plate tectonic story without considering a model of a different kind, that is a model to describe how major scientific advances take place. Your model—if you had ever thought about one before starting this Course—might well have been that scientific advances take place by researchers diligently chipping away at a vast block of hitherto unknown facts and laws. Furthermore, you may also have thought that scientists amass vast amounts of data, and then produce generalizations from these. After reading the preceding account of the development of plate tectonics, you should have begun to realize that science is not as simple, or as boring, as this.

In 1962, at the same time as the major developments in the Earth sciences were taking place, a historian of science, Thomas Kuhn, published a book entitled *The Structure of Scientific Revolutions*, which suggested an alternative to the view that science progresses by the gradual accumulation of new facts and formulation of new theories. Kuhn suggested that many major advances in science take place via revolutions, which are preceded by a period that he called *normal science* and signalled by a period of *extra-ordinary science*.

He likened normal science to 'puzzle-solving'; it is research firmly based on one or more past scientific achievements that are generally acknowledged as supplying the foundation on which new work can be based. However, there may come a time when researchers divide into different schools of thought, and a period of uncertainty, or crisis, ensues. Extra-ordinary science begins when one of the 'competing' ideas takes over, because it enables a whole range of previously puzzling phenomena to be satisfactorily explained.

This complete change, or revolution, in attitudes and beliefs, is followed by a 'mopping-up' phase during which existing and new data are re-interpreted. Such 'mopping-up' operations, according to Kuhn, are what engage most scientists throughout their careers and constitute normal science.

Do you think developments in the Earth sciences during this century fit Kuhn's revolutionary model? Think back over what you have studied in these two Units; Table 5 should help you do this. Spend at least half an hour considering this question, and see if you can achieve the following Objectives:

(a) Outline events in the revolution in Earth sciences in terms of periods of 'normal science', 'crisis', 'breakthrough', and 'mopping-up' (SAQs 16, 17 and 18).

(b) Explain why Wegener's concept of continental drift took more than 50 years to become generally accepted by Earth scientists (SAQ 19).

(c) Summarize the technological and political developments that contributed to the formulation of the revolution in the Earth sciences (SAQ 20).

Now answer SAQs 16–20. Write about 100 words for each answer.

SAQ 16 (*Objective* (*a*)) What was the generally accepted view concerning the origin of the Earth and its major surface features at the turn of the century?

SAQ 17 (*Objective* (*a*)) Do you think the Earth sciences went through a period of uncertainty concerning the origin of continents and oceans?

SAQ 18 (*Objective* (*a*)) When do you consider that the revolution in the Earth sciences occurred?

SAQ 19 (*Objective* (*b*)) Why do you think Wegener failed to convince geologists of the validity of the continental drift hypothesis? What evidence did he lack that became available later to convince sceptics?

SAQ 20 (*Objective* (*c*)) What technological and political developments influenced the collection of new evidence in favour of continental drift, and the later hypotheses of sea-floor spreading and plate tectonics?

TABLE 5 Some key events and contributions in the development of the plate-tectonic theory

	Key developments	Participants mentioned in this Unit (or earlier Units)
Late nineteenth and early twentieth century	Ideas on Earth history dominated by the idea that the Earth was cooling down from an original molten state	
1896	Discovery of radioactivity	
1911	First summary of radioactive dates of rocks published	Holmes
1915	First edition of *The Origin of the Continents and Oceans*	Wegener
1920s	Several major debates on continental drift; most workers anti-drift, with only geologists in southern hemisphere generally favouring the idea	Du Toit
1931	Publication of paper proposing that continental drift is driven by convection currents in the mantle powered by heat from radioactive minerals	Holmes
Late 1950s	Ocean exploration: discovery of East Pacific Ridge, median rift valleys of ocean ridges; relative youthfulness of guyots; heat-flow studies	Hess, Bullard
	Palaeomagnetic data supports drift theory	Blackett, Runcorn (R 06)
	Inclined zones of earthquakes discovered around Pacific	Benioff
1960, 1962	Geopoetry: sea-floor spreading described first, named later	Hess, Dietz
1963	First magnetic reversal time-table proposed	Cox and others (Unit 5)
	Magnetic anomaly pattern over ocean ridges related to magnetic reversals and sea-floor spreading	Vine and Matthews
	Two leading journals reject paper relating oceanic magnetic anomaly patterns to reversals and spreading	Morley
1965 onwards	Mass of evidence described supporting Vine–Matthews hypothesis	
1965	Transform-fault concept proposed	Wilson
1967/68	New global tectonics proposed and 'verified'	Morgan; Le Pichon; Isacks, Oliver and Sykes; McKenzie and Parker
1968	Deep-Sea Drilling Project confirms, by sampling, age of S. Atlantic Ocean floor predicted by Vine–Matthews hypothesis	

There are three lessons to be learnt from this brief diversion into the history of science. One is that progress in science does not appear to take place at a gradual and constant pace. The second is that individuals make their mark on science by a combination of diligence, imagination—and good fortune. And the third lesson is that a revolutionary idea that appears to be indisputable to one generation of scientists may be toppled by the next:—witness what happened to late nineteenth-century ideas of a contracting Earth less than 100 million years old!

Further reading

Gass, I. G., Smith, P. J., and Wilson, R. C. L. (eds.) (1972) *Understanding the Earth*, 2nd edn, Artemis Press. Prepared as a set book for S100*, it contains a number of chapters that explain in more detail the material considered in Units 6 and 7 (Chapter 16, Sea-Floor Spreading, by F. J. Vine; Chapter 19, Plate Tectonics, by E. R. Oxburgh).

Wyllie, P. J. (1976) *The Way the Earth Works*, John Wiley & Sons. An excellent book that covers much the same grounds as S101, Units 4–7. It also contains a review of arguments against the new global geology.

Geological Museum (1972) *The Story of the Earth*, HMSO. A small, cheap (less than £1) lavishly illustrated colour booklet summarizing the 'new geology'.

Sullivan, W. (1977) *Continents in Motion: the New Earth Debate.* Macmillan, London. An extremely readable account of geology's revolution, from Wegener to the present day, written by a science journalist who attended many of the discussion meetings of the 1960s. Easily comprehended by readers without any geological background.

Hallam, A. (1973) *A Revolution in the Earth Sciences*, Clarendon Press. This book reviews the events that are described in Units 6 and 7 and discusses whether recent developments in the Earth sciences are an example of Thomas Kuhn's scientific revolution. This book is comparatively short (127 pages) but assumes that its readers have a reasonable geological vocabulary.

Acknowledgements

Grateful acknowledgement is made to the following sources for material used in these Units:

Figures 2a, 16a, 46c (left) and 47e National Environmental Research Council by permission of the Director of the Institute of Geological Sciences; *Figures 2b and c and 3a* Aerofilms; *Figure 3b* NASA; *Figure 17* J. C. Holden; *Figures 18a and b* from A. Holmes (1931) *Trans. Geol. Soc. Glasg.*, Vol. 18; *Figure 18c* from A. L. Du Toit (1937) *Our Wandering Continents*, Oliver & Boyd; *Figures 19, 38 and 44* from P. J. Wyllie (1976) *The Way the Earth Works*, John Wiley; *Figure 20* E. Bullard; *Figure 21* from B. C. Heezen, 'Deep-sea Floor' in S. K. Runcorn (ed.) (1962) *Continental Drift*, Academic Press; *Figures 22a and b* from M. N. Hill (ed.) (1962) *The Sea*, Vol. 3, John Wiley; *Figure 26* from A. N. Strahler (1963) *The Earth Sciences*, Harper and Row; *Figure 27* from A. E. Maxwell (ed.) (1970) *The Sea*, Vol. 4, Wiley-Interscience, by permission of A. E. Langseth; *Figure 30a* Geological Survey of Great Britain. Crown Copyright; *Figure 30b* U.S. Coast and Geodetic Survey; *Figure 31* Geological Society of America; *Figure 34b* from F. J. Vine and D. H. Matthews (1963) 'Magnetic anomalies over ocean ridges' in *Nature*, Vol. 199, Macmillan; *Figure 35 a–d* from F. J. Vine, 'Magnetic anomalies associated with mid-ocean ridges', pp. 73–89 in R. A. Phinney (ed.) (1968) *The History of the Earth's Crust*, Princeton University Press; *Figure 35e* from J. R. Heirtzler (1968) 'Sea-floor spreading' in *Scientific American*, copyright © 1968 Scientific American Inc. All rights reserved; *Figures 36, 41, 42 and 53* from I. Gass *et al.* (1972) *Understanding the Earth*, 2nd edn, Artemis Press; *Figure 37a* Scripps Institution of Oceanography; *Figure 37b* National Science Foundation; *Figure 37c* from M. Talwani *et al.* (1976) *Initial Reports of the Deep-Sea Drilling Project*, Vol. 38 National Science Foundation; *Figures 46a, 47b and c* from The Geological Museum (1973) *The Story of the Earth.* Reproduced by permission of the Controller of HMSO; *Figure 46c (right)* from W. S. Broecker (1974) *Chemical Oceanography*, Harcourt, Brace, Jovanovich Inc., and by permission of C. D. Hollister, Woods Hole Oceanographic Institute; *Figure 47d* Peter Francis.

* The Open University (1970) S100 *Science: A Foundation Course*, The Open University Press.

Aims and Objectives

Apart from Objective 1, which relates to all the terms and concepts used in this Unit, the Objectives may be divided into three groups which are related to the Aims of this Unit as follows:

Aims

1 (*Objectives 2–4 and 6*)
To describe the major features of the Earth's crust and its surface.

2 (*Objectives 5 and 7–11*)
To describe the theory of 'plate tectonics' and summarize the evidence and lines of reasoning that underpin it.

3 (*Objectives 12–14*)
To describe how the development of the plate tectonic theory was influenced by technological and political developments, and why it can be considered as a 'scientific revolution'.

Objectives

1 Define in your own words, illustrate by sketches, or recognize correct definitions or illustrations of the terms and concepts listed in the fourth column of Table A (SAQs 1 and 2).

2 Explain why the continued existence of continents for at least three thousand million years implies a mobile outer part to the Earth (SAQ 3).

3 Describe the difference between the layman's concept of oceans and continents and that understood by Earth scientists (SAQ 4).

4 Describe the major patterns shown by the Earth's topographic features, ages of continental and oceanic rocks, and the distribution of seismic and volcanic activity (SAQ 5).

5 Correctly list, or recognize from given examples, the major lines of evidence that support the continental drift hypothesis (SAQ 6).

6 Demonstrate your understanding of the concepts of isostasy and gravity anomalies by interpreting given data concerning actual and hypothetical crustal models (ITQ 1 and SAQs 7 and 8).

7 Demonstrate your understanding of the hypothesis of sea-floor spreading by summarizing the evidence that supports it, and by carrying out calculations based on sea-floor magnetic anomaly data (SAQs 9–12).

8 Describe the plate tectonic hypothesis (SAQ 13).

9 Describe the evidence that favours the plate tectonic hypothesis (SAQ 14).

10 Draw on a map of the world the location of the six major lithospheric plates, and indicate whether their boundaries are constructive or destructive (ITQ 10).

11 Distinguish constructive and destructive plate margins on the basis of their contained rock types, structures and geophysical characters (ITQ 11 and SAQ 15).

12 Outline events in the revolution in Earth sciences in terms of periods of 'normal science', 'crisis', 'breakthrough', and 'mopping-up' (SAQs 16–18).

13 Explain why Wegener's concept of continental drift took more than 50 years to become generally accepted by Earth scientists (SAQ 19).

14 Summarize the technological and political developments that contributed to the formulation of the revolution in the Earth sciences (SAQ 20).

ITQ answers and comments

ITQ 1 The value of g would be *above* the normal value at a stage when the growth of the volcanic island would have taken place much faster than could be compensated for by isostatic adjustment. Thus the volcanic island would be characterized by a *positive* gravity anomaly indicating a localized excess of mass. Once isostatic adjustment was complete, the value of g over the site would return to the value it had before the island began to form.

ITQ 2 Benioff zones occur beneath regions of *explosive* volcanic activity; you should already be familiar with the association of such activity inland from trenches (see Question 6 on page 14).

ITQ 3 The revised rate of movement on one limb of the convection cell is approximately $2.3\,\text{cm}\,\text{yr}^{-1}$ (that is, an opening of 5×10^8 cm in 11×10^7 years, which is a total opening rate of approximately $4.6\,\text{cm}\,\text{yr}^{-1}$ or $2.3\,\text{cm}\,\text{yr}^{-1}$ on one limb of a convection cell).

ITQ 4 Evidence in favour of upwelling convection currents underlying ocean ridges includes:

(a) high heat-flow values in these regions (see Figure 27);

(b) active volcanism and seismicity along ocean ridges (see Figures 9 and 10);

(c) the fact that ridges are topographic 'highs' rising above the general level of the ocean basins suggests that they are less dense regions, this lowered density being due to expansion caused by higher temperatures.

ITQ 5 If Hess's speculation that oceans are replaced by new mantle material every 300 to 400 Ma is correct, then there should be no rocks older than this present on the ocean floors. When he wrote his paper, Hess knew that rocks no older than about 120 Ma had been found in the oceans, and so used this as evidence in favour of his hypothesis. More recent work, as you will see, has only slightly extended this figure to 160–170 Ma, so it seems that Hess's figure of 300 to 400 Ma was an over-estimate.

ITQ 6 Wegener envisaged the continents floating on the mantle (although he did not use the latter term) to be like ice-floes floating on water. So Hess's concept was completely different—to him oceanic and continental crust behaved as *one* slab forming the outer part of a convection cell.

ITQ 7 (a) The leading edges of continents 'are strongly deformed ...' Mountain belts ringing the Pacific are examples of such deformation.

(b) 'The oceanic crust, buckling down ...' The inclined zones of earthquake activity (Benioff zones) are interpreted as evidence for this process.

ITQ 8 If Hess's speculations were correct, mantle material would be rising under the Juan de Fuca Ridge to produce new oceanic crust. As this material moved sideways on each side of the Ridge, it would cool past the Curie point of any magnetic materials present, thus 'freezing' the polarity of the Earth's magnetic field into the rock at any given instant. As the polarity of the field changed (see Unit 5, Figure 23 and right-hand side of Figure 33 in these Units), so would the resultant remanent magnetism of the new oceanic crust material. Thus the oceanic crust would become magnetized in directions alternately identical to and opposed to the present-day magnetic polarity. This means that the effect is either to subtract or to add approximately one per cent to the present-day magnetic field, which produces the magnetic stripe anomalies observed (shown in Figure 31b). Note that the normal polarity event at about 1.6 Ma (the Gilsa event) was too short-lived to produce a significant magnetic anomaly on the sea-floor, and so it does not appear on either Figure 31 or 33.

If you worked out the answer to this question at your first attempt, you were doing very well! Do not worry if you had difficulty in understanding this explanation; the next part of the text and TV 07 will explain it in more detail. You may have been surprised that the authors of the 1961 paper that described the magnetic anomaly patterns in the Eastern Pacific did not propose this explanation. They did not do so for two reasons. First, at the time they did not have access to data concerning the detailed topography of the region, because they were still held as top secret by the U.S. Coast and Geodetic Survey (the topographic expression of the Juan de Fuca Ridge identified on Figure 31b was revealed at a later date when the information was published). Second, Hess's 'essay in geopoetry' was not formally published until 1962, although it had been widely circulated in pre-print form before that time.

ITQ 9 Figure 50 is an annotated version of Figure 39, showing that slippage of one block of oceanic crust past another *only occurs between points A and B*. To the left of A, both segments of crust are spreading away from the ridge (A–A′, B–B′) at the same rate, and the same situation applies to the right of B. The fault between A and B is known as a *transform fault*, and it is a feature unique to oceanic crust. Traces of the former positions of the faults (or, strictly, one side of the fault) that are now seismically inactive show up as topographic features (fracture zones) on the *World Ocean Floor* chart. (AX, BX′ on Figure 50).

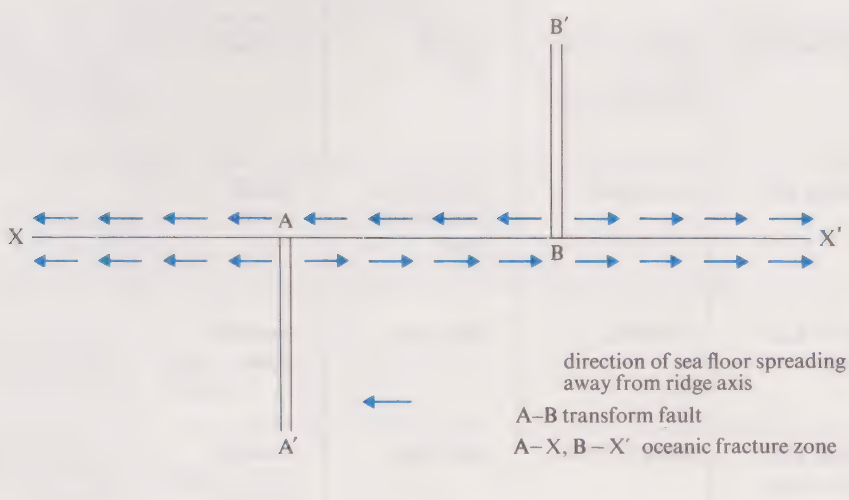


FIGURE 50 An annotated version of Figure 39, for use with the answer to ITQ 9.

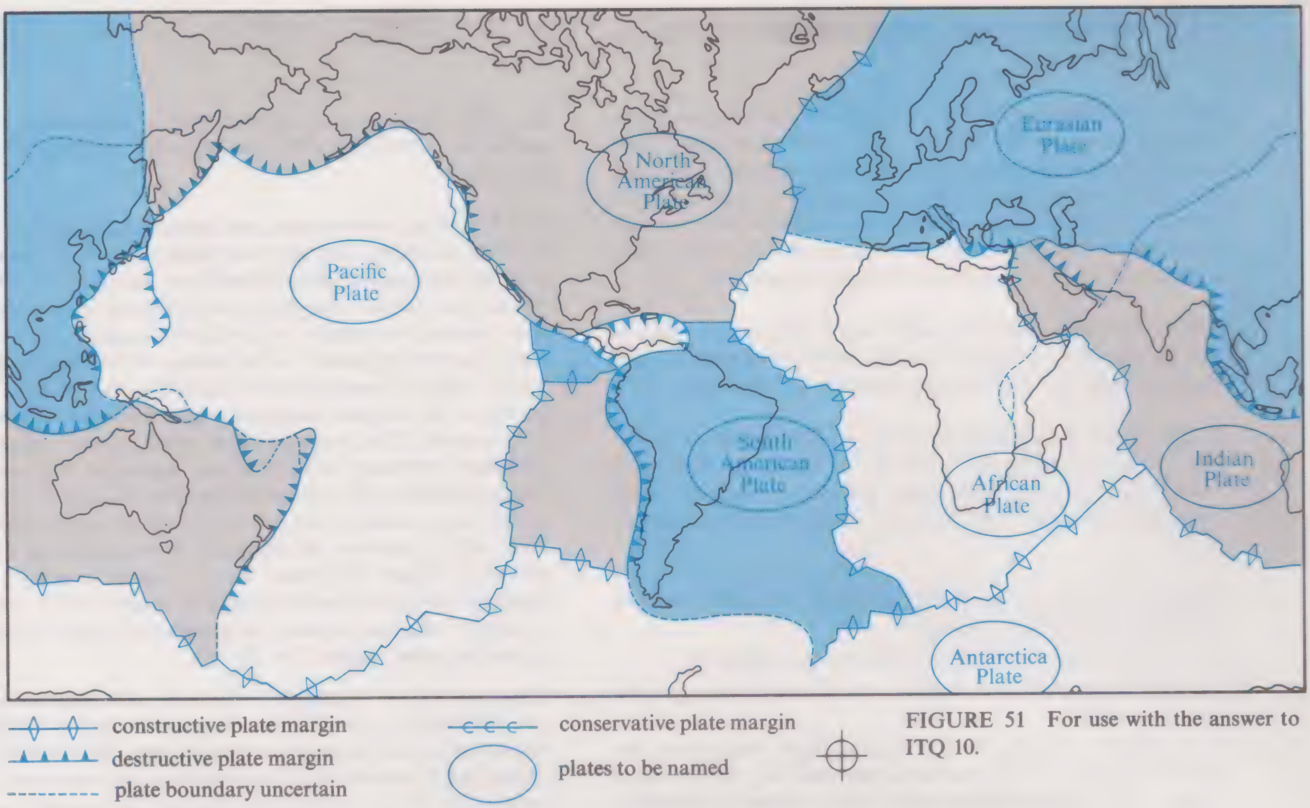


FIGURE 51 For use with the answer to ITQ 10.

ITQ 10 Figure 51 shows the distribution of constructive and destructive plate boundaries you should have marked on Figure 45.

ITQ 11 Your completed Table 4 should look like Table 6.

TABLE 6

	Topography	Age of rocks (0–10 Ma, 10–100 Ma, or > 1000 Ma)	Seismic activity (shallow-, intermediate- or deep-focus)	Volcanic activity (effusive or explosive)	Other notable features, such as heat flow (high, average, low) or gravity anomalies
Constructive plate margins	ocean ridge with median rift valley, and rugged topography	0–10 Ma	shallow	effusive	high heat flow
Destructive plate margins Ocean/ocean	trench/island arc	mostly 10–100 Ma	Benioff zone	explosive	low heat flow in trench; negative gravity anomaly over trench
Ocean/continent	trench/mountain belt	mostly 0–100 Ma older on continental side	Benioff zone	explosive	low heat flow in trench; negative gravity anomaly over trench
Continent/continent	mountain belt	very variable	shallow and intermediate focus	usually absent	
Mid-plate regions Continental	relatively flat, cratons	> 1000 Ma	very little	generally absent, except in rift regions	average heat flow; no marked gravity anomalies
Oceanic	relatively flat, abyssal plains	mostly 0–100 Ma	very little	generally absent, except for some oceanic islands (e.g. Hawaii)	average heat flow; no marked gravity anomalies

SAQ answers and comments

SAQ 1 See Figure 52.

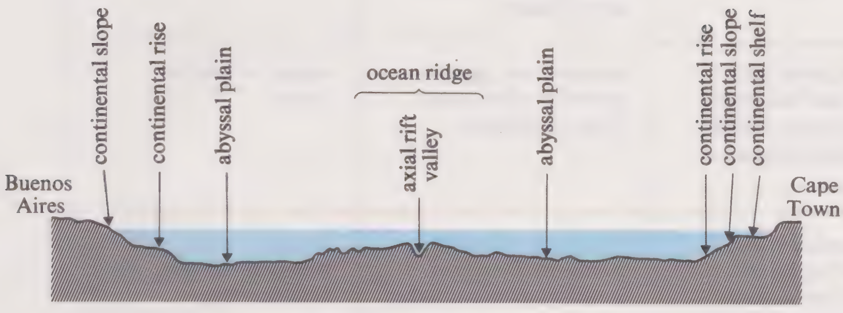


FIGURE 52 The answer to SAQ 1.

SAQ 2 Your completed Table 2 should look like Table 7.

TABLE 7

	Topography	Age of rocks	Seismic activity	Volcanic activity
Continental features				
Cratons	0–3 km, relatively flat	old > 1000 Ma	virtually absent	none
Young mountain belts not bordering oceans	rugged, 3–8 km	generally less than 60 Ma, trending EW from Mediterranean to Tibet and China	very active; mostly shallow, but deeper foci in Mediterranean region	rare; except in Mediterranean area, where there is explosive activity
Young mountain belts bordering oceans	rugged, 3–6 km	Rockies: 100–200 Ma; Andes younger	very active; shallow on ocean side, becoming deeper inland (Benioff zones)	very active; explosive in nature
Oceanic features				
Ocean-basin floors	3–5 km below sea-level; flat and smooth	60 to over 100 Ma	very little	very little; except for a few volcanic islands which are effusive
Ocean ridges	3–5 km above ocean basin floors, rugged, traversed by fractures, and some ridges have central rift valley	very young–youngest rocks (0–10 Ma) occur	active; shallow foci only	active; effusive
Ocean trenches	up to 11 km below sea-level, 5 km below ocean basin floors	relatively young and variable (not discussed so far in the text)	active; associated with zones of shallow–intermediate–deep-focus earthquakes	associated island arcs or mountain belts have explosive volcanic activity

SAQ 3 The existence of continents as discrete slabs dotted about the globe suggests that some process must have operated to segregate the lighter granitic crust of which they are composed. This, coupled with the existence of continents and mountain belts for 3 000 Ma despite continued erosion, suggests processes operating within the Earth that continually 'renew' the continents.

SAQ 4 To the layman, the terms ocean and continent mean that the first is an area of the Earth covered by the sea, whereas the second is dry land. To the geologist, the wet–dry distinction has little significance; what is more important to him is the fact that the Earth has two 'preferred levels' as shown by the frequency distribution plot in Figure 5 (p. 12). Seismic studies show that these two levels are underlain by crust of different densities, the higher level (the continental platform) being floored by less dense crust than that beneath the lower one. The division into continental and oceanic crust is probably marked by the central steeper part of the cumulative frequency curve (the continental slope).

SAQ 5 Your completed Table 3 should look like Table 8.

TABLE 8

	Geographical distribution	Patterns/associations	Regions where absent or rare
Rocks older than 1 000 Ma	only in cratons such as Baltic, Canadian and African shields	found in central parts of continents; seismic and volcanic activity largely absent	unknown in ocean basins
Rocks younger than 100 Ma	bulk of ocean floors of this age; mountain belts of circum-Pacific and Alpine Himalayan Belts	oceanic rocks get progressively older away from ocean ridges	virtually absent on cratons
Effusive volcanic activity	along central parts of oceanic ridges; on African craton, and scattered within ocean basins away from trenches	equidistant between bordering continents in Atlantic Ocean; linked with shallow-focus seismic activity	on other cratons, and largely absent from young mountain belts
Explosive volcanic activity	circum-Pacific ring of fire	usually associated with ocean trenches and deeper-focus earthquakes	central part of ocean basins, most cratons
Zones of shallow earthquake foci	circum-Pacific belts, Alpine Himalayan Belt and ocean ridges	associated with effusive volcanism along ocean ridges; explosive volcanism along mountain belts and island arcs	cratons, ocean basin floors
Zones of intermediate and deep-focus earthquakes	circum-Pacific belt	get deeper in direction outward from central Pacific; associated with explosive volcanic activity	cratons, ocean basins

SAQ 6 The four major lines of evidence that support the continental drift hypothesis are:

1 topographic fit of continents;

2 match of ancient mountain belts between continents;

3 palaeoclimatic evidence;

4 similarities between fossils found on now-separated continents;

SAQ 7 In Figure 24, woodblocks (a) and (c) are depressed lower than block (b), and so are characterized by negative gravity anomalies, with (c) having the larger of the two. Blocks (d) and (e) are higher in the water than (b) and so are the sites of positive gravity anomalies, with (d) the larger of the two.

SAQ 8 The northern Baltic Sea region is characterized by a negative gravity anomaly, because the crust has not yet risen enough to fully compensate for the weight of ice that has melted. Therefore there is a mass deficiency beneath this region.

SAQ 9 At 1 400 km out from the ocean ridge, the ocean floor is interpreted to be 77 Ma old, that is, the spreading rate = 1400 km/77 Ma = 1.8 cm yr^{-1}.

SAQ 10 The 10 Ma anomaly can be traced through to the 350 km location as shown on Figure 53.

SAQ 11 The spreading rate is 3.5 cm yr^{-1} (350 km/10^7 yr).

SAQ 12 Again, you need to trace the 30 Ma 'marker' through from the South Atlantic, as shown on Figure 53. The 10 Ma age was located in SAQ 10 at 350 km: the 30 Ma point is 700 km out from the ridge crest, so, in the period between 10 and 30 Ma ago, 350 km of ocean floor was formed. Therefore the spreading rate was 1.75 cm yr^{-1}, slower than the following 20 Ma period (at 3.5 cm yr^{-1}).

SAQ 13 You should have completed the blanks in the description of plate tectonics as follows:

Ocean floor is envisaged as continuously accreting to a *rigid* (a) plate which is *seismically* (b) inactive, and which interacts with other plates along active zones of *volcanism* (c) and seismicity. The movement of the plates over the surface of a *sphere* (d) can be described with reference to a *pole* (e) of rotation. *Transform* (f) faults trend along the direction of *small* (g) circles about the *pole* (e) of rotation, whereas ocean ridges between these faults trend along *great* (h) circles passing through the poles (e). There are three types of plate boundary (the order in which you used these terms does not matter): 1 *constructive* (i); 2 *destructive* (j); 3 *conservative* (k). Along the first type, new *crust* (l) is formed by *sea-floor spreading* (m). Along the second type, oceanic crust and upper mantle are being *subducted* (n).

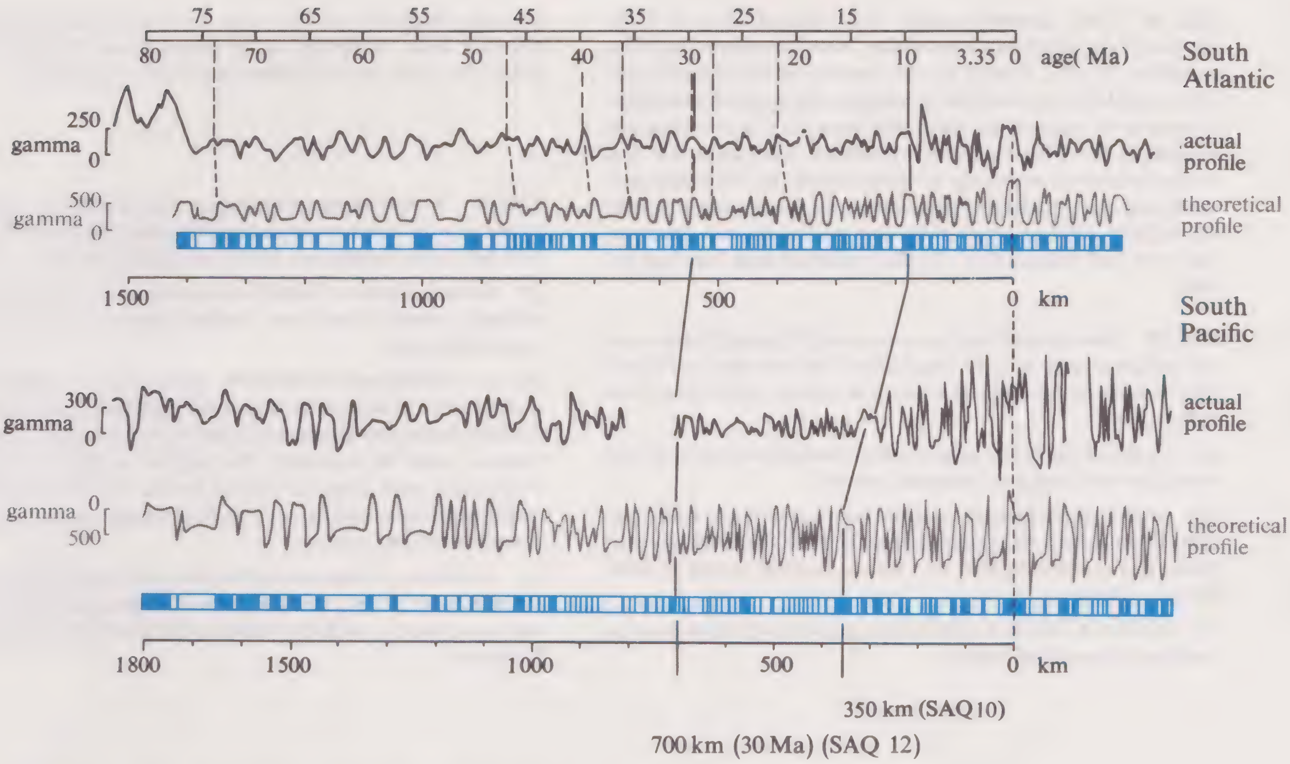


FIGURE 53 For use with the answer to SAQs 10 and 12.

SAQ 14

1 B, C, E. Palaeoclimatic and palaeomagnetic data contributed to the confirmation of the continental drift hypothesis, as did the computer fitting of the topography of continental margins.

2 Items A and D (deep-sea drilling and ocean-floor magnetic anomalies) confirmed the sea-floor spreading hypothesis, which is a corollary of drift. So you might have been tempted to choose these two under (1). You should have also chosen G, the magnetic polarity reversal timetable.

3 The concept of transform faults was confirmed by detailed studies of magnetic anomaly patterns (D), and so the formulation of the magnetic polarity reversal timetable is also relevant (G), but most of all by studies of earthquake first motions along the lines of oceanic fracture zones (F).

4 It could be said that all the items support the idea of plate tectonics. But earthquake first-motion studies (F) provide direct evidence concerning the *directions of movement* of the crustal plates at the present time.

SAQ 15

Constructive margins

1	2 ✓	3 ✓	4
5	6	7	8
9	10	11 ✓	12 ✓
13 ✓	14	15 ✓	16 ✓

Destructive margins

ocean/ocean (island arc)

1	2 ✓	3	4 ✓
5 ✓	6	7 ✓	8 ✓
9 ✓	10 ✓	11	12
13	14	15 ✓	16

ocean/continent (Andean)

1	2	3	4 ✓
5	6 ✓	7 ✓	8 ✓
9 ✓	10 ✓	11	12
13	14	15	16

SAQ 16 At the turn of the century, most geologists believed that the Earth was still cooling down after its birth as a molten ball from the Sun. This implied that it was contracting, which would mean that continents were more likely to be coming together rather than drifting apart. In addition, researchers were wary of any ideas that smacked of catastrophism; they were content to interpret the Earth's features in terms of processes that could be observed in action at the present time.

SAQ 17 The publication of Wegener's book in 1915 signalled the start of a period of uncertainty about the origin of continents and oceans, which hitherto had been largely thought of in terms of vertical, rather than horizontal movements. But until the late 1950s the majority of geologists were not disciples of Wegener. Only when palaeomagnetic results gave the geophysicists evidence (which they had collected) that continents wandered, did they begin to reconsider their belief that the Earth was too rigid for major lateral movements to have occurred in its crust. Thus the real crisis period was in the late 1950s and early 1960s.

SAQ 18 Hess's geopoetry paper, which was published in 1962, but widely circulated two years earlier, marks the beginning of the revolution. In 1963, ideas of sea-floor spreading and magnetic polarity reversals were combined to interpret the magnetic anomalies observed over ocean ridges. After 1968 there was a torrent of papers confirming the Vine–Matthews hypothesis, using data that had been accumulated during the previous decade. By 1968, plate tectonics was being considered seriously by Earth scientists, who then entered into a 'mopping-up phase' and applied the new theory to both new and existing data. So the revolution took less than ten years.

SAQ 19 There are perhaps two reasons why Wegener's ideas were not accepted until over 50 years after they were first published. Firstly, some of the evidence he cited in support of his theory was rather shaky:

(a) he placed too much faith in actual measurements of drift; the technique was simply not accurate enough;

(b) some of his biological evidence, both modern and fossil, was open to more than one interpretation, because the distribution of plants and animals depends on climatic controls as well as links between continents;

(c) he did not present *detailed* evidence or maps to show how the continents once fitted together.

Secondly, Wegener—and all other Earth scientists at the time—had very little knowledge of the ocean floors. Such knowledge proved to be the key to confirming the drift hypothesis.

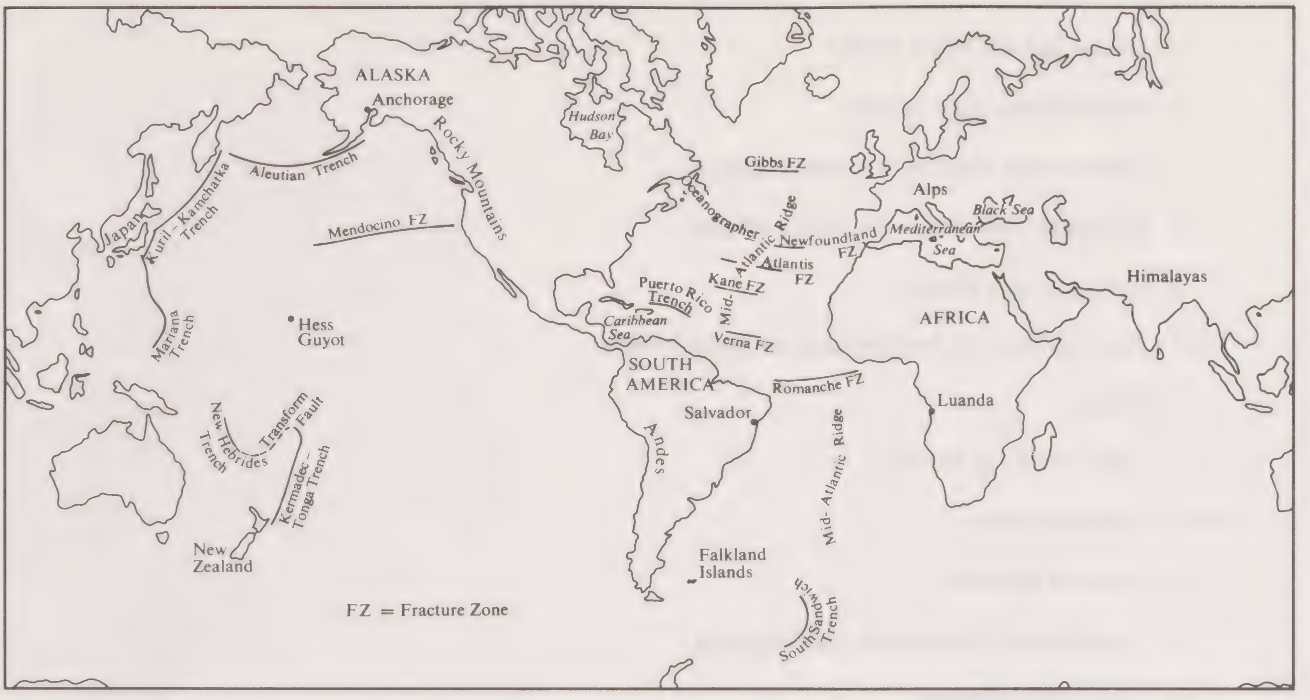
SAQ 20 The following technological and political developments helped to obtain new evidence that favoured continental drift, and later led to the formulation of the new global tectonics:

(a) the development of sensitive magnetometers for airborne and seaborne surveys arose from wartime research concerning submarine detection;

(b) the development of sensitive seismic arrays enabled earthquake foci to be accurately pinpointed (including their depth) and the first motions associated with them to be determined. Thus plate motions could be measured. The impetus to develop such new instruments came from the need to be able to distinguish natural earthquakes from underground nuclear explosions, and so 'police' a nuclear test ban treaty;

(c) techniques of deep-sea drilling owe their initial development to the Mohole project, which for a period during the 'cold war' was seen as a race to reach the Mohorovičić discontinuity before the Russians.

KEY to *World Ocean Floor* chart



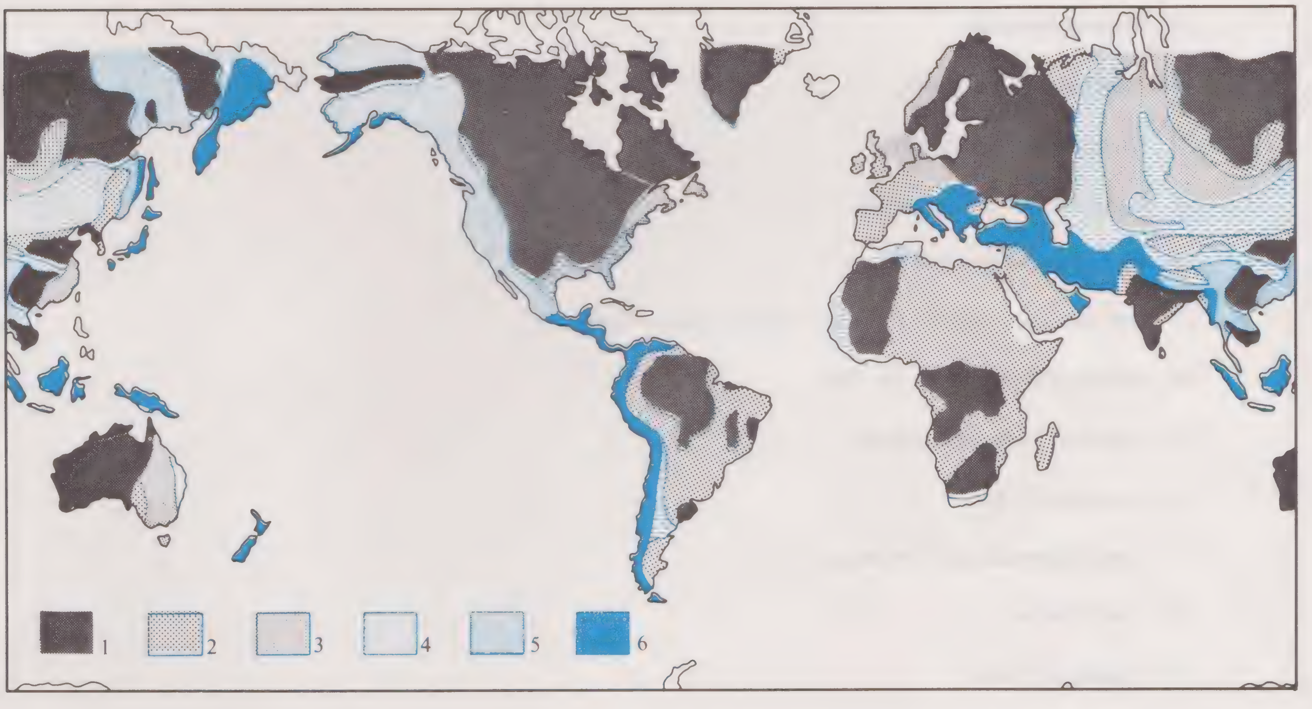


FIGURE 7 Map showing the distribution of ages of rocks on the continents formed during past phases of mountain building. The way in which rocks can be dated will be discussed in detail in Unit 26.

1 Rocks formed more than 1 000 Ma ago; these regions, termed *cratons*, have remained unaffected by earth movements for a considerable period, and they form the stable 'nuclei' of the continents (Audio-vision sequence 'Crustal patterns'). Such regions exhibit a relatively subdued relief in contrast to the rugged topography associated with 'young' mountain belts such as the Alps, Andes, Himalayas and Rockies (see 5 and 6 below).

2 Rocks formed 1 000–600 Ma ago;

3 Rocks formed 600–400 Ma ago;

4 Rocks formed 350–250 Ma ago;

5 Rocks formed 200–100 Ma ago;

6 Rocks formed 60 Ma ago to the present.

You will see from the above intervals of rocks that there were gaps between the main phases of mountain-building.

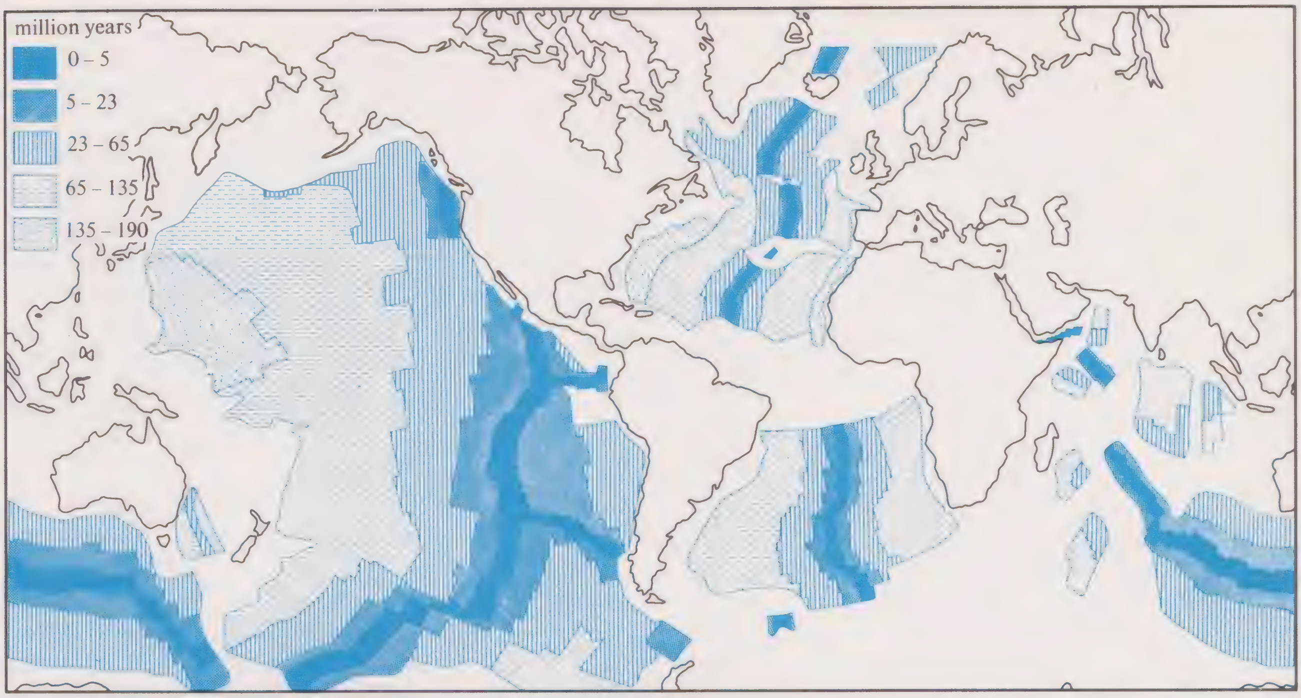


FIGURE 8 Map showing the age of the ocean basins, as determined by studies of magnetic anomalies. Blank areas are those in which there are insufficient data to support the interpretation of ocean floor ages. The magnetic anomaly interpretation method is described on pages 44–48.

FIGURE 9 Map showing the distribution of active subaerial volcanoes. Black dots show the occurrence of *effusive* volcanoes, whose activity is dominated by outpourings of liquid lava (see specimen S3 in your Home Experiment Kit). Blue dots signify *explosive* activity, produced by the release of large amounts of gas as the lava nears the vent of the volcano; the resultant rock types include volcanic ash and lava containing abundant gas bubbles (see specimen S2 in your Home Experiment Kit). The Audio-vision sequence 'The origin of rocks' (associated with Unit 4) described these two types of activity in more detail.

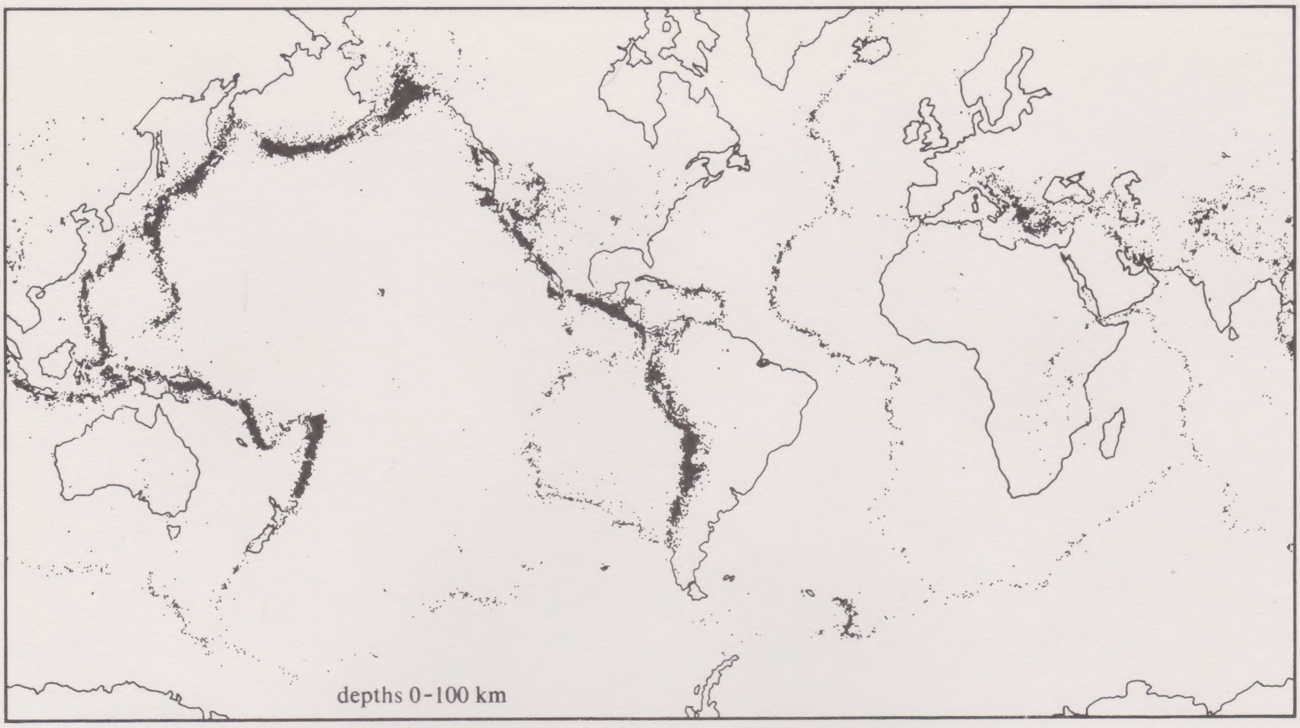


FIGURE 10 Map showing the distribution of all shallow (less than 100 km depth) earthquake foci recorded between 1961 and 1967.

FIGURE 11 Map showing the distribution of all *intermediate*-focus (100–300 km depth, black dots) and *deep*-focus (300–700 km depth, blue dots) earthquakes recorded between 1961 and 1967.

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